A Synthesis of Adult Sockeye Salmon Migration and Environmental Observations for the Somass Watershed, 1974-2012

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A SYNTHESIS OF ADULT SOCKEYE SALMON MIGRATION AND ENVIRONMENTAL OBSERVATIONS FOR THE SOMASS WATERSHED, 1974-2012

by

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ABSTRACT

Hyatt, K.D., Stiff, H.W., Stockwell, M.M., Luedke, W., Rankin, D.P., Dobson, D., and Till, J. 2015. A synthesis of adult Sockeye salmon migration and environmental observations for the Somass watershed, 1974-2012. Can. Tech. Rep. Fish. Aquat. Sci. 3115: vii + 199 p.

Daily mean air and water temperature, stream discharge, and adult Sockeye migration data were assembled for Sproat Lake and Great Central Lake Sockeye stocks returning to the Somass watershed, British Columbia. A continuous regional air temperature index was statistically related to intermittent water temperature observations to hind-cast daily water temperature trends at several sites (lower Somass River, Sproat Falls, Stamp River Falls) from 1918-2012. Statistical relations between discharge observations were used to extend discontinued discharge records at the Somass and Stamp Falls sites based on the continuous series (1913-2012) available from the Sproat River site. Peak-over-threshold analyses were applied to reconstructed time-series to review trends in extreme temperature and flow. Daily mean water temperature and discharge were correlated with Sockeye migration rates at the Sproat Falls and Stamp Falls fishways.

Daily mean water temperatures exceeding 19-21°C at two sites (Stamp and Sproat Falls) were associated with stopped or reduced migration, especially during extended low flow periods. At Stamp Falls, a high proportion (70%) of upstream migration activity occurred at river temperatures of 18-19°C and discharge levels of 20-50 cms. However, peak daily migration rates occurred at combinations of lower water temperatures (16-18°C) and higher discharge levels (60-90 cms).

Fifty to eighty-five percent of Sproat migration activity (days) occurred when Sproat River daily mean temperatures were above 18-20°C. Above average flows (>30 cms) may enable Sproat Sockeye to withstand stressful water temperatures during the 3-km migration interval in the Sproat River, which is typically 1-2°C warmer than the relatively cool waters at the confluence of the Somass-Sproat rivers (<21°C) and at depth in Sproat Lake (<15°C hypolimnetic water). Highest daily migration rates were associated with temperatures of 17-22°C and flows of 32-36 cms. At Sproat discharge levels <22 cms, maximum migration rates occurred at no more than 18°C.

The frequency and duration of "warm" weather episodes (daily mean temperature >20°C) have steadily increased in the Somass area since the 1950's, with corresponding increases in the frequency and duration of equivalent "warm" water periods observed to be stressful (reduced migration rates) or lethal (mass mortalities in 1990 and 2004) to fish in the Stamp and Sproat rivers. Given results in this report, climate change projections do not auger well for sustainable production of Somass system Sockeye salmon in decades beyond 2050 in the absence of human interventions (e.g. creation of additional water storage, engineering of "cold-water" release structures for the Somass, Stamp and Sproat rivers) to mitigate for trends in environmental conditions that, left unaddressed, will most certainly decrease future migration success of adult Sockeye salmon.

RESUMÉ

Hyatt, K.D., Stiff, H.W., Stockwell, M.M., Luedke, W., Rankin, D.P., Dobson, D., et Till, J. 2015. A synthesis of adult Sockeye salmon migration and environmental observations for the Somass watershed [Synthèse des observations sur l'environnement et la migration du saumon rouge adulte du bassin hydrographique de la rivière Somass], 1974-2012. Rapp. tech. can. sci. halieut. aquat. 3115: vii + 199 p.

On a rassemblé les données sur la montaison des stocks de saumon rouge des lacs Great Central et Sproat qui retournent dans le bassin hydrographique de la rivière Somass, en Colombie-Britannique. Ces données portent sur les températures quotidiennes moyennes de l'eau et de l'air, le débit des cours d'eau et la migration des saumons rouges adultes. On a rapproché statistiquement un indice continu de la température de l'air régionale et les observations intermittentes sur la température de l'eau afin de prévoir *a posteriori* les tendances de la température quotidienne de l'eau pour plusieurs sites (cours inférieur de la rivière Somass, chutes Sproat, chutes de la rivière Stamp) de 1918 à 2012. On a utilisé les relations statistiques entre les observations du débit pour reconstituer les registres de débit discontinus des sites de la rivière Somass et des chutes Stamp à partir des séries continues (1913-2012) du site de la rivière Sproat. On a appliqué des analyses des dépassements des seuils aux séries chronologiques reconstituées afin d'examiner les tendances des températures et débits extrêmes. Les valeurs moyennes quotidiennes de la température et du débit de l'eau ont été mises en corrélation avec les taux de migration du saumon rouge à la passe à poissons des chutes Sproat et des chutes Stamp.

Des températures quotidiennes moyennes de l'eau supérieures à 19-21 °C à deux sites (chutes Stamp et chutes Sproat) étaient associées à un arrêt ou à une baisse de la migration, notamment durant les longues périodes de faible débit. Aux chutes Stamp, une bonne partie de la montaison (70 %) a eu lieu lorsque la température de la rivière était de 18-19 °C et le débit de 20 à 50 m^3/s. Toutefois, les pics quotidiens de migration surviennent lorsque la température de l'eau est plus basse (16 à 18°C) et le débit plus élevé (60 à 90 m^3/s).

De 50 à 85 % des activités de migration dans la rivière Sproat (en jours) ont lieu lorsque la température quotidienne moyenne de l'eau dépasse les 18-20 °C. Il est possible que les débits supérieurs à la moyenne (> 30 m^3/s) permettent aux saumons rouges de la rivière Sproat de résister à des températures de l'eau stressantes pendant ces 3 km de migration, cette rivière étant habituellement 1 à 2 °C plus chaude que les eaux relativement fraîches au confluent des rivières Somass et Sproat (<21 °C) et dans le lac Sproat, en eau profonde (<15 °C dans les eaux hypolimniques). Les taux de migration quotidiens les plus élevés sont associés à des températures de 17 à 22 °C et à des débits de 32 à 36 m^3/s. Quand le débit de la rivière Sproat est inférieur à 22 m^3/s, les pics de migration surviennent lorsque la température de l'eau ne dépasse pas les 18 °C.

Depuis les années 1950, la fréquence et la durée des épisodes de « chaleur » (température quotidienne moyenne supérieure à 20 °C) dans la région de la rivière Somass augmentent régulièrement. Cette augmentation s'accompagne d'une hausse de la fréquence et de la durée des périodes équivalentes de température « chaude » de l'eau des rivières Stamp et Sproat, ce qui peut stresser les poissons (baisse des taux de migration), voire les tuer (mortalités massives en 1990 et en 2004). Compte tenu des résultats de ce rapport, les prévisions liées au changement climatique s'annoncent peu encourageantes en ce qui concerne la viabilité de la production de saumon rouge de la rivière Somass dans les décennies après 2050 en l'absence d'interventions humaines (p. ex., création d'un réservoir d'eau supplémentaire, construction de structures de rejet « d'eau froide » pour les rivières Somass, Stamp et Sproat) visant à atténuer les tendances des conditions environnementales qui, si elles ne sont pas gérées, réduiront très certainement le succès de la migration du saumon rouge adulte à l'avenir.

INTRODUCTION

Maintaining healthy and diverse populations of salmon that will support sustainable fisheries in the present and for future generations is the key goal of the Department of Fisheries and Oceans' Wild Salmon Policy (DFO 2005). This goal is advanced by safeguarding the genetic diversity of wild salmon populations, maintaining habitat and ecosystem integrity, and managing fisheries for sustainable benefits.

However, management methods to meet sustainable fisheries and biodiversity objectives are likely to be affected by climate change impacts on the distribution, abundance, and productivity of wild salmon populations (Finney et al. 2002). Therefore, conservation, restoration, and harvest management of many wild salmon populations will require improvements in knowledge of the extent to which human disturbance versus natural disturbance events control variations in salmon growth, survival, and production.

Within the general category of natural disturbance regimes or events, annual and seasonal variations in freshwater temperature and flow represent the most common factors exerting a major influence over salmon life history outcomes. Analyses of historical data indicate that significant changes in regional meteorological factors (such as air temperature and precipitation) that directly affect freshwater quantity and quality have already occurred in response to climate change in Canada's Pacific region (e.g., Whitfield and Cannon 2000; Whitfield 2001; Whitfield, Bodtker and Cannon 2002), and regional climate model projections point to increased changes in these factors through the 21st century (Abdul-Aziz, Mantua and Myers 2011; Littell et al. 2011).

Recent investigations in the Pacific Northwest and British Columbia have demonstrated regional temperature shifts of about 0.8°C over the past century, with projected temperature increases of 1.5-3.2°C in near-future decades (Mote et al. 2003). Seasonal precipitation has also changed markedly in the recent past (Walker and Sydneysmith 2008), and future projections point to wetter winters and drier summers, with a high likelihood that extreme events involving regional temperature and precipitation will become more frequent (Mantua, Tohver, and Hamlet 2010; IPCC 2007). These analyses also indicate that the magnitude, and, in some cases the direction, of historical and projected climate variability, exhibit sub-regional specificity due to the large and topographically complex areas involved (Walker and Sydneysmith 2008).

Temperature effects on migrating adult Sockeye (*Oncorhynchus nerka*) have been well documented in many river systems in the Pacific Northwest (McCullough et al. 2001; Hyatt et al. 2003; Nelitz et. al. 2007; Salinger and Anderson 2006). Lethal temperatures are reported in the range 21-24°C, and water temperatures in excess of 18°C may affect migration speed, cause timing delays, and alter spatial distribution of Sockeye salmon. Increased water temperature also may result in secondary effects such as increased disease, resulting in pre-spawn mortality (Cooke et al. 2004; Hinch and Martins 2011). Thermal stress has also been found to reduce salmon gamete viability, fertilization rates and decrease egg to fry survival rates (Jensen et al. 2004). Since Sockeye populations may also differ in their thermal tolerances, reflecting local adaptation to conditions over their historic evolution (Farrell 2009; Martins et al. 2012), stock-specific responses to climate variation and change impacts are also possible(Martins et al. 2010).

Stream discharge levels may also be associated with variations in migration timing, causing delays, affecting swimming speed, and inducing biological stress during upstream migration of adult salmonids (Hinch and Bratty 2000). The quantitative effects may differ between water bodies due to unique physical stream attributes (rapids and falls, canyons, etc., but also man-made fish-ways and weirs) which influence water velocity in key locations along the migratory route. In some cases, low flows may result in physical limits to fish passage; in other cases, high flows may generate velocity barriers that reduce or prohibit upstream migration.

The current report is one of a series intended to consolidate and document historic observations on key life history events and associated environmental variables for relatively data-rich Sockeye and Chinook salmon populations distributed throughout their range in Canada's Pacific region (Stiff et al. 2013, 2015a, 2015b, 2015c; Damborg et al. 2015). Although there are many potential uses for these data, the focus of our current work is to develop life-stage specific models that identify potential associations between salmon production variations and climate variation effects in freshwater and marine ecosystems throughout the eastern rim of the north Pacific.

STUDY AREA

The Stamp/Somass watershed was selected for initial investigation due to its' long history of salmon stock assessment and environmental monitoring activities (Hyatt and Steer 1987). Salmon escapement, fry or smolt abundance, associated biological traits and environmental data (temperature, flow, water quality) for this system have been gathered by reliable methods over at least the past 30 years. Wild Sockeye Salmon along with Chinook, originating from Robertson Creek Hatchery, have assumed roles as important indicators of productivity trends likely to be exhibited by a wider range of wild salmon populations from the west coast of Vancouver Island. Thus, given appropriate qualifiers, analysis of outcomes of interactions between environmental variations and "indicator stock" life history events may be used as a predictive tool to anticipate environmental change and life history consequences for regionally proximate but 'data poor' watersheds and salmon populations.

The Somass watershed drains an area of about 1,426 km² into Alberni Inlet, a coastal fjord 54.3 km long on southwestern Vancouver Island (Figure 1). The watershed is characterized by a marine west coast climate, designated *Cfb* in the *Koppen* classification system, and characterized by mild winters, warm summers, and long spring and autumn seasons with small seasonal ranges in temperature (Peel, Finlayson and McMahon 2007). The climate is distinguished by several factors: the mean temperature ranges between 0°C and 22°C; and even the driest month of the year receives more than 30 mm of precipitation on average.

The climate in the northeastern Pacific undergoes multi-decadal changes which affect climate variables such as air temperature and precipitation in the Somass watershed. The *Pacific Decadal Oscillation* index[1], based on sea surface temperature, indicates that the ocean was relatively cool from 1947-1976, and relatively warm from 1977 to 1998 (Mantua and Hare 2002). Since 1999, the PDO has been predominantly in cool phase, but has shifted every few years between phases, making it currently difficult to determine if the 1998 shift was a true shift to a cold phase (Climate Impacts Group, Univ. Washington, unpub. data, 2014[2]). While the first half of the 2000s was predominantly in the warm phase, cool phase conditions have predominated since 2006 (ibid).

The Somass watershed consists of three major sub-basins: the Sproat system (387.5 km² in area), dominated by Sproat Lake, which drains into the Sproat River (mean daily flow 37.9 cms)[3]; the Great Central system (651 km²), dominated by Great Central Lake, which drains into the Stamp River (mean daily flow 58.9 cms)[4]; and the Ash River (388 km²), draining Oshinow and Elsie lakes (mean daily flow 16.7 cms)[5] also into the Stamp River. The Somass River, formed by the merger of the Stamp and Sproat rivers, has a mean daily flow of 121.4 cms.[6,7]

As part of a kraft pulp-mill effluent study, Tully (1949) evaluated Somass River discharge impacts on dissolved oxygen concentrations in the Somass Estuary and Alberni Harbour. Low discharge rates were correlated with low oxygen concentrations which can be lethal to fish and other aquatic life (Birtwell et al. 1983; Eby et al. 2005; Kidwell et al. 2009). As a result, flow controls in the Somass watershed were implemented, coincident with pulp-mill production in 1956, to help maintain adequate dissolved oxygen levels in Alberni Harbour as a rearing, migration, and/or holding area for high value salmon species (Chinook, Sockeye, Coho) originating from the Somass watershed. The original mill owner, MACMILLAN BLOEDEL LTD. (now CATALYST PAPER CORPORATION, CPC), constructed a dam at the outlet of GCL providing 98.7 million cubic meters of seasonal lake storage to maintain a minimum Somass River flow of 26.6 m³/s (940 cfs), in support of mill effluent dilution standards. This was accompanied by construction of a low-head weir at the outlet of Sproat Lake, connected by overland pipeline to Port Alberni, to provide a reliable source of water for the kraft pulp-mill operation.

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[1] The Pacific Decadal Oscillation (PDO) is a pattern of Pacific climate variability that shifts phases on an inter-decadal time scale, usually about 20 to 30 years. The PDO is detected as warm or cool surface waters in the Pacific Ocean, north of 20°N. During a "warm", or "positive", phase, the west Pacific becomes cool and part of the eastern ocean warms; during a "cool" or "negative" phase, the opposite pattern occurs (Mantua and Hare 2002).

[2] http://cses.washington.edu/cig/pnwc/compensopdo.shtml#pdoensoyears

[3] Sproat River Hydrological Station 08HB008, 1913-2012.

[4] Stamp River Hydrological Station 08HB009, 1914-1978.

[5] Ash River Hydrological Station 08HB023, 1959-2005.

[6] Somass River Hydrological Station 08HB017, 1957-2002.

[7] Hydrological data are available from ENVIRONMENT CANADA's WATER SURVEY DIVISION website at: http://www.wsc.ec.gc.ca/index_e.cfm.

Robertson Creek Hatchery (RCH), located on the upper Stamp River near the outlet of GCL, has been in operation since 1972 and is now one of the largest federal SALMONID ENHANCEMENT PROGRAM (SEP) facilities on the BC Coast. Chinook, Coho and Steelhead are the main species produced with annual releases of as many as 10M, 1M, and 100K juveniles, respectively. Hatchery personnel also conduct an annual program of inorganic nutrient additions to Great Central Lake to enhance Sockeye production (Hyatt et al. 2004; Hyatt et al. 2011). Production levels for the four species combined make the Stamp/Somass the largest fish producer on Vancouver Island, with sport, commercial and First Nations fisheries worth millions of dollars annually to the Port Alberni and BC economies.

At Stamp Falls, the site of a natural obstruction to fish migration on the Stamp River, a concrete vertical slot fish-way was constructed in 1927 and upgraded in 1954, allowing virtually unimpeded access for all salmon species to the upper watershed and GCL (Hyatt and Steer 1987). Prior to 1927, it is thought that salmon, with the exception of summer run steelhead, were generally restricted to habitats below Stamp Falls. Consequently, prior to 1927, Sproat Lake was the major source of Sockeye returning to the Somass system. During several decades following construction of the Stamp Falls fishway, catches and escapement of GCL Sockeye increased to values averaging no more than 50,000 fish (i.e. total returns <100,000, Hyatt and Steer 1987). Catches and escapements to GCL increased to an average of more than 150,000 fish (i.e. total returns >300,000 fish) from the early 1970s to present in association with salmon enhancement projects. Notwithstanding these major fish production developments, Somass River Sockeye escapement over the last three decades has been highly variable, with annual returns of 150,000 to 1,000,000 fish, and an all-year average of ~350,000 spawners split between the Sproat and GCL stocks (DFO 2012).

Each year since 1975, adult and jack Sockeye have been electronically enumerated on an hourly basis at fishways at one or more of Stamp Falls, Sproat Falls or the outlet of Great Central Lake. Daily records of fish passage have been archived as unpublished data of DFO South Coast Area after in-season and post-season assembly and review by stock assessment personnel. These records serve here as the basis for a retrospective analysis of annual Sockeye migration performance in relation to seasonal water temperature and discharge variables.

METHODS

DATA ASSEMBLY AND ANALYSIS

Sockeye Migration Data

Daily sockeye escapement estimates for Great Central (1976-2012) and Sproat Lake (1974-2012) stocks are provided by FISHERIES AND OCEANS CANADA.[8] These data are collected in-season and finalized post-season by DFO personnel as follows:

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[8] Great Central and Sproat Lake sockeye adults, jacks, and total sockeye are collated in a Microsoft Excel® spreadsheet (EscDay.xls) maintained by DFO South Coast personnel (D. Dobson, J. Till, K. Hyatt, DFO; unpub. data).

Total daily sockeye migrants are estimated for each stock from hourly counts using Pulsar™ electronic fish counters installed at the Great Central Lake fishway (approximately 32 km upriver of the Somass estuary) and the Sproat Falls fishway in the Sproat River (approximately 15 km above the Somass estuary) (Figure 1, Figure 2). Raw, hourly, electronic fish-counts are summed by date, and adjusted for daily estimates of jack (small age-3 adults) percentages and non-sockeye based on: twice-weekly visual calibrations of machine count accuracy, estimates of uncounted migrants bypassing the counters[9], and biological sampling for size, sex and age by species (J. Till, DFO, pers. comm.). The combined totals of daily adult (i.e. large, >40cm, age-4 and older) and jack (i.e. small, <40cm age-3) migrant estimates for each stock are retained for subsequent analyses.

Beginning in the first week of September, the GCL electronic counters are removed to allow upstream passage of Chinook salmon which are too large to pass through the tunnel banks of Pulsar counters. At this point, all salmon passing through the Stamp Falls fishway are recorded on videotapes, subsequently analyzed by trained and experienced observers, who identify fish species, jack proportions (based on fish size), and proportions of marked fish (adipose-fin clipped Chinook). Video observations are thought to be typically greater than 95% accurate for counts, species identification, and mark rate (J. Till, DFO, pers. comm.). Stamp Falls daily video count data are appended to the GCL-fishway daily count time-series assuming a one-day lag between counter sites.

Data issues identified in the sockeye migration data, and remedied prior to analysis in the import process, include:

- negative escapement values (e.g., Great Central total sockeye, 07-Aug-1997; Sproat total sockeye, 01-July-1997), which were replaced with a zero;
- unlikely zero counts (e.g., GCL, 21-Jul-2000), which were replaced by an interpolated value from preceding and succeeding dates;
- prolonged electronic counter failures in 2010 at the Sproat fishway (July 6, 7, 13-15, 20-31, August 1-3, 11, 24-26, September 3-4, 22-26, 30), and the GCL fishway (August 6-8, 11-12, 18 and 24), for which all dates with less than 16 observations of hourly counts were omitted;
- false peak migration date(s)[10] in early September, attributed to upstream

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[9] Though bypass at the GCL fishway is an uncommon event (attributed to infrequent dislodging of fishway screens), migrants bypassing the Sproat fishway may make up a significant but variable portion (5-30%) of the Sproat escapement as fish routinely jump the falls during low summer flows (J. Till, DFO, pers. comm.).

[10] Annual GCL escapement estimates also include a tally of manual observations obtained from Stamp River swim surveys between the Stamp Falls and GCL fishways to account for fish that are not tallied at either fishway during the interim period between termination of the electronic counters at the GCL fishway and startup of Stamp Falls video monitoring. However, no data are available regarding the daily timing for these migrants through the GCL fishway. As the swim survey counts are generally added to the last date of GCL fishway counts in the source data (for final spawner totals estimation),

swim survey count data aggregated into a single date (e.g., Great Central Lake, 05-Sep-2002, 04-Sep-2003, 10-Sep-2004, 08-Sep-2005, 07-Sep-2006, 06-Sep-2007, 03-Sep-2009, 02-Sep-2010, and 01-Sep-2011; J. Till, DFO, pers. comm.). These values were reduced to known GCL count data for those dates, or replaced with estimates interpolated from preceding and succeeding dates; and

- erroneous date shifts in the MS-Excel dataset (relative to the original MS-Access database source), including a one-day offset for GCL sockeye (04-Aug-1982 to 08-Aug-1982). The dates for these data were shifted to coincide with the source data (MS-Access database) prior to analysis.

To standardize the annual adult migration time-series for inter-year and inter-stock comparisons, daily percentages of Sproat and Great Central sockeye stock migrants were calculated relative to the total annual stock escapement. Annual plots of daily migration rate (% relative to the annual total escapement) were generated, overlaid with historical mean and maximum daily migration rate by Julian day-of-year, for inter-annual migration pattern comparisons.

Univariate statistical analyses were used to characterize the distributions of migration effort by adult sockeye. Properties examined included central tendency (mean, median, modal date of passage), scale (range, variance, extreme values and outliers), and shape (skewness, kurtosis) of annual migration effort distributions at the location of interest. Median (50th percentile) and 75th quartile values of the historical datasets were calculated to establish low (0-75th percentile), medium (75-90th percentile) and high (90-100th percentile) categories for daily migration rate classification. Quartiles of the Julian dates of migration in the historical data were used to categorize daily migrant data into early (0-25th percentile), middle (25-50th percentile), and late (75-100th percentile) observations. Daily migration rate (%) data were transformed using the arcsin function to normalize the percentage data where appropriate for parametric analyses (Sokal and Rohlf, 1969).

For the purposes of aligning daily sockeye migration timing with environmental variables at key points in the freshwater migratory route (e.g., Papermill Dam in the lower Somass River, fish-ways and counter sites in the Stamp and Sproat Rivers), migration dates were lagged under the assumption that Somass sockeye in freshwater migrate at 8.7 km/d (Manzer, Morley, and Girodat 1985). For example, to align GCL migrant data with Stamp River Fishway temperatures and flow levels approximately 14 km downstream, 2 days were subtracted from the GCL counter date. To align stock migrant data with lower Somass temperatures and flow levels, 5 days were subtracted from the GCL counter date, and 3 days were subtracted from the Sproat counter date. Where environmental data were coincident with migration data (e.g., Sproat counts, temperatures, and discharge readings adjacent to the

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artificially inflating the daily migrants estimate for that date, swim survey data must be excluded from migration pattern analyses. Thus, for the purposes of this analysis, daily adjusted counts for the final GCL counter date are restricted solely to daily fishway estimates, if available. If unavailable, the tally for any dates including swim survey counts is replaced by an interpolated value based on previous and next dates.

Sproat River Fishway), no date lags were applied.

Environmental Data

Physical data, including air temperature, precipitation, and water temperature were assembled from existing electronic databases, published documents, unpublished reports and personal records from a variety of sources including government agencies (e.g., B.C. MINISTRY OF ENVIRONMENT, Canada's DEPARTMENT OF THE ENVIRONMENT, WATER SURVEY OF CANADA, and FISHERIES AND OCEANS Canada), public utilities (B.C. HYDRO) and industry (CATALYST PAPER CORPORATION), as well as private and non-governmental organizations.

Basic statistical analyses were required to collate and describe the available data, establish relationships between regional air and site-specific water temperature datasets, and define inter-site relations for both water temperature and discharge datasets to infill missing observations. STATISTICAL ANALYSIS SOFTWARE (SAS® Version 9.2; 2008) was used to analyze the data. The resulting datasets were stored in a relational MICROSOFT ACCESS® FRESHWATER ENVIRONMENTAL VARIABLES DATABASE and are available from DFO upon request.[11]

River Discharge

Total daily discharge (cms) data for the Somass watershed were obtained from the archives at the WATER SURVEY OF CANADA (WSC) website.[12] WSC stations utilized in this analysis include:

- *Somass near Port Alberni* (Station 08HB017, 49°17'7"N x124°52'0"W, 1957-2003, with the exception of blocks of missing data in 1969, 1970, and 1973);
- *Stamp River near Alberni* (above the Sproat River confluence) (Station 08HB010, 49°20'6"N x 124°55'15"W, 1913-1978); and
- *Sproat River* (Station 08HB008, 49°17'23"N x 124°54'37"W, 1913-2011). Real-time WSC data are also available for the Sproat River station for 2012, which were appended to the Sproat River data for this analysis.

With the exception of the real-time data, these datasets undergo detailed quality-control analysis before posting to the WSC web site.

The *Sproat River* station (Station 08HB008) was selected as the hydrometric reference site on the basis of its active status, extended record length (1913-present), and limited level of regulation[13]. Though discharge data collection has been intermittently re-instated near the *Somass River* site as of 2008[14] and near

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[11] Contact Howard.Stiff@dfo-mpo.gc.ca or Kim.Hyatt@dfo-mpo.gc.ca.

[12] Environment Canada – Water Survey of Canada website: http://www.wsc.ec.gc.ca/applications/H2O/HydromatD-eng.cfm.

[13] A low-head weir (overflow dam) at the outlet of Sproat Lake supports provision of water for CPC's Port Alberni pulp mill operation, and fish passage in Sproat River (Figure 2).

[14] Preliminary Somass River discharge data (station 08HB017) for 2008-2009 were made available by Northwest Hydraulics Consultants (Barry Chilbeck, nhc, pers. comm.).

Stamp Falls since 2010[15], missing blocks of data in 1969, 1970, 1973 and from 2003-present necessitated reconstruction of Somass discharge based on the active hydrological *Sproat River* time-series. Similarly, estimates were required for missing flow data for the *Stamp River* station time-series, which terminated in 1978.

However, Sproat River is hydrologically smaller than the Stamp/Somass waterbodies, resulting in challenges in establishing simple inter-site flow models. At moderate flow levels, discharge volumes in the Sproat River are approximately one-third of those in the lower Somass (Table 5), and about half those at Stamp Falls (Table 3). Linear, log-linear, and curvilinear (parabolic) models were used to derive station-to-station discharge relations for reconstruction of missing station values, as follows:

1. Statistical models were employed to develop station-to-station discharge equations for the much larger Somass waterbody[16] as a function of same-day Sproat River[17] discharge. Models included the simple linear model ($Y = A + BX$); a non-linear log model ($Y = AX^B$); and a curvilinear model ($Y = A + BX + CX^2$). Data were restricted to the summer months (July-September) to focus on the water levels relevant to migrating sockeye. Calibration data were partitioned from the datasets by selecting every 10th daily observation; this also served to reduce the error associated with parametric analyses of auto-correlated time-series. Validation data were based on all data. The most appropriate model was selected based on goodness of fit tests, and correlation analysis was used to compare predicted discharge time-series with available observed discharge data.
2. A similar process was followed for reconstructing missing Stamp River flows, though this was hindered by the fact that Stamp flows[18] are affected by regulated discharge from the outlet dam at Great Central Lake. During very low Sproat flows, Stamp flows were often maintained at an approximate late summer minimum level of 20 cms under regulated operations. Lack of correlation between the sites at lower flows was partially alleviated by restricting the data analysis to 1960-2012 (post-dam construction). Best estimates of missing Stamp flows were based primarily on the relatively linear Somass-to-Stamp relationship, followed by infilling of remaining missing Stamp data using the best-fit Sproat-to-Stamp discharge model.

Air Temperature

Environment Canada's Meteorological Services group maintains an archive of climate, hydrographic and water quality data gathered from both active and inactive stations distributed throughout British Columbia and the Yukon. Station locations and data descriptions can be found at the ENVIRONMENT CANADA (EC) climate data archive[19]. This web site was accessed to identify potential sites of air temperature data within the area of interest (Figure 2) for statistical analyses with water temperature data. Climate station 1090230 (*Alberni Robertson Creek*) was ultimately selected for data retrieval on the basis of (i) the quantity and quality of data available; (ii) proximity to key habitat locations used by one or more life history stages of Somass salmonids; and (iii) the potential to routinely update data (i.e. *Robertson Creek* is an "active" climate station). In addition, stations *Alberni Lupsi Cupsi* (1030210), *Shuhum Creek* (1036218), *Port Alberni* (1036205), *Port Alberni Airport* (1036206), and automated station *Port Alberni AUT* (automated 1036B06) were identified as locations that could provide supplementary, temporally-overlapping historical data from which the *Alberni Robertson Creek* period of record could be extended (Figure 2). As a final resort, data from the nearest AHCCD[20] station, *Estevan Point*, were obtained to infill any remaining minor data gaps (< 3 days).[21]

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[15] BCCF data loggers in 2010 – 2012 (Pellett et al. unpub.); DFO data loggers in 2013 (pers. comm. C. McConnell, DFO).

[16] Somass River drainage area: 1,280 km^2 (WSC)

[17] Sproat River drainage area: 351 km^2 (WSC)

[18] Stamp River drainage area: 899 km^2 (WSC).

For the majority of Canadian climate stations, air temperature measurements are taken from self-registering, maximum and minimum thermometers that record the extremes of each parameter within a 24-hour period. Daily mean temperature, where provided, is defined as the average of the maximum and the minimum temperatures attained during the 24-hour period. Daily maximum, minimum, and mean air temperature, and total daily precipitation data were downloaded as electronic files[22] from ENVIRONMENT CANADA'S CLIMATE DATA SERVICES at Canadian Climate Data Online[23]. These datasets undergo detailed quality-control analysis before posting to the web site.

ROBERTSON CREEK "STANDARD" AIR TEMPERATURE INDEX

Reconstruction of an historic, long-term, freshwater thermal regime requires a set of daily mean air temperature records spanning multiple decades. Climate records for *Alberni Robertson Creek* do not commence until February 1, 1961; however, data from nearby station *Port Alberni* (1036205) are available for July 1, 1917 through

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[19] ENVIRONMENT CANADA Climate Data: http://climate.weatheroffice.gc.ca/climateData/canada_e.html

[20] ENVIRONMENT CANADA has refined the air temperature and precipitation time-series for certain stations, as part of the ADJUSTED AND HOMOGENIZED CANADIAN CLIMATE DATA (AHCCD) group of climatological stations across Canada. These data incorporate a number of adjustments applied to the original station data to address shifts due to changes in instruments and in observing procedures, thus optimizing their use for research including climate change studies (Vincent et al. 2012; Vincent and Gullett 1999).

[21] AHCCD Licence Agreement: This work contains data licenced "as is" under the Government of Canada Open Data Licence Agreement. Such licencing does not constitute an endorsement by the Government of Canada of this product.

[22] Robertson Creek air temperature and precipitation data were originally downloaded on 27 May 2003, and data for Port Alberni and Alberni Lupsi Cupsi were originally retrieved 30 Sep 2003. Data updates for these stations and all data for Shuhum Creek, Port Alberni Airport, and Port Alberni AUT were retrieved 29 Feb 2008.

[23] http://climate.weather.gc.ca/index_e.html

October 31, 1960. Strong correlations in air temperature due to the geographic proximity among regional weather stations enabled the development of a series of linear regressions to incorporate data from the nearby stations into a "ROBERTSON CREEK STANDARD" station – a single regional daily air temperature time-series with a continuous period of record spanning July 1, 1917 to December 31, 2012. *Alberni Lupsi Cupsi* climate records (November 1, 1948 through December 1, 1974) were necessary to provide a bridge between the *Port Alberni* and *Robertson Creek* data sets, according to Equation 1 and Equation 2, in the following manner:

Least squares linear regression was used to establish the relationship for daily mean air temperatures at *Lupsi Cupsi 1030210* (LC) as a function of *Port Alberni 1036205* (PA):

Equation 1 : $LC = 0.952 \cdot PA - 0.614$ ($r^2 = 0.96$, $n = 3996$, $p < 0.001$)

The above equation was used to infill daily mean air temperature for missing LC dates prior to 1961, and to extend the LC air temperature time-series back to 1917.

A second linear regression was developed to establish the relationship for daily mean air temperatures at *Robertson Creek* as a function of *Lupsi Cupsi* (1961-1974):

Equation 2 : $RC = 1.034 \cdot LC - 1.176$ ($r^2 = 0.98$, $n = 4852$, $p < 0.001$)

Equation 2 was used to infill daily mean air temperature for missing RC dates from 1961 to 1974, and to extend the RC air temperature time-series back to 1917.

Similar least squares regression equations were developed to establish the relationship between daily mean air temperatures at *Robertson Creek* and the *Port Alberni Airport* (PAA) (1980-1995) (Equation 3), *Shuhum Creek* (SHU) (1987-2000) (Equation 4), *Port Alberni AUT* (1994-2007) (Equation 5), and *Estevan Point* (AHCCD station 1032730, 1924-2012) (Equation 6) to estimate *Robertson Creek* air temperatures for missing dates from 1924 to December 31st, 2012:

Equation 3 : $RC = 1.066 \cdot PAA - 0.925$ ($r^2 = 0.98$, $n = 5413$, $p < 0.001$)

Equation 4 : $RC = 1.003 \cdot SHU - 0.083$ ($r^2 = 0.99$, $n = 4222$, $p < 0.001$)

Equation 5 : $RC = 1.019 \cdot AUT - 0.093$ ($r^2 = 0.98$, $n = 4514$, $p < 0.001$)

Equation 6 : $RC = 1.530 \cdot EST - 5.014$ ($r^2 = 0.85$, $n = 3158$, $p < 0.001$)

The ROBERTSON CREEK STANDARD "station" was thus assembled as a continuous table of daily mean air temperatures for the time period 01-Jul-1917 to 31-Dec-2012, where:

1. Daily air temperatures for July 1917 through December 1960 were calculated from Equation 1 and Equation 2;
2. Daily air temperatures for February 1961 through December 2012 were collected at Environment Canada climate station *Alberni Robertson Creek 1030230*, and;
3. Missing data between January 1961 and December 2012 were calculated from Equation 2 to Equation 5 based on data availability. Where multiple

sites of data were available, the relationship demonstrating the highest correlation coefficient was used.

4. Missing dates between 1924 and 2012[24] were in-filled from AHCCD station *Estevan Point* according to Equation 6.

Temperature and precipitation data for the ROBERTSON CREEK STANDARD are periodically updated from ENVIRONMENT CANADA station *Alberni Robertson Creek 1030230* at http://climate.weatheroffice.ec.gc.ca/climateData/canada_e.html, and stored in a relational MICROSOFT ACCESS® FRESHWATER ENVIRONMENTAL VARIABLES DATABASE, available from DFO upon request.[25]

MULTI-DAY MEAN AIR TEMPERATURE INDICES

The best predictive air-water relationships exist for associations between daily mean water and multi-day mean air temperature (Hyatt and Stockwell 2003; Webb and Nobilis 1997). Hyatt and Stockwell (2003) found that a 10-day cumulative moving average temperature (MAT) produced the maximum correlation with daily mean water temperature. Ten-day MATs are calculated such that the value at day *n* is the average of daily means from day *n* - 9 to day *n* inclusive. This form of moving average is referred to as a *backward* moving average, since it is effectively a cumulative average of past observations only.

The ten-day backward moving average air temperature (10d BMAT) does, however, introduce two forms of bias into the resulting estimated daily mean air temperature, either of which may influence the correlative and predictive capacity of air/water temperature relationships.

One effect of using *backward* moving averages is a temporal displacement of temperature changes (such as peaks and troughs) later than their actual occurrence. However, a *centered* moving average (e.g., a 10-d CMAT, from day *n* – 5 to *n* + 5) affects multi-day means such that peaks and troughs align more accurately with the original daily mean air temperature time series. Thus, multi-day CMATs derived from the ROBERTSON CREEK STANDARD daily mean time-series were utilized in this study for correlative analyses with site water temperatures.

MAT indices calculated over extended periods also lead to a reduction in the day-to-day variability in the resulting temperature time-series. To evaluate the effects of period length in the multi-day mean air temperature index, the "observed" mean daily Robertson Creek air temperature time-series was compared to four multi-day mean indices derived from *centered* moving average periods (3d-CMAT, 5d-CMAT, 7d-CMAT and 10d-CMAT).

Correlation analysis was used to identify the most appropriate multi-day CMAT index for estimation of missing daily mean water temperature at each water temperature site, by comparing Pearson correlation coefficients for the five different regional air temperature indices specified above, with daily mean water temperatures from high-resolution data logger data sets for a representative subset of the available years of air/water temperature data, designated as a calibration dataset. Selection of data for the calibration data set was based on subjective and statistical examinations of the annual air and water temperature time-series plots and annual regression relationships. Years with consistent and apparently unbiased data logger readings associated with a maximum range of temperature values for both warming and cooling periods[26] were preferred for characterizing the all-year air/water temperature relationship. The remaining data were used for validation of statistical relations.

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[24] AHCCD data were only available from 1913-2011; 2012 data from online unadjusted *Estevan Point* station 1032730 were appended to the time-series until AHCCD data become available.

[25] Contact Howard.Stiff@dfo-mpo.gc.ca or Kim.Hyatt@dfo-mpo.gc.ca.

The multi-day ROBERTSON CREEK STANDARD CMAT index with the lowest adjusted Akaike Information Criterion (AICc) and the highest Pearson correlation coefficient for calibration data was used for subsequent air/water temperature regression relations. Although the 10-d CMAT index was included in this assessment, and (usually) generated the maximum correlation, this index was ultimately discarded in favour of the 7-d CMAT due to the undesired trade-off between high correlation versus the dampening effect of the 10-d CMAT on day-to-day air temperature variation, described above.

Univariate statistical analyses were used to characterize the selected air temperature index for the period of historical migration data i.e., number of observations, central tendency (mean, median, mode, etc.), variation (range, variance, extreme values and outliers), and shape (skewness, kurtosis)). A threshold exceedance analysis, tallying the decadal mean monthly frequency of dates for which the multi-day air temperature index exceeded 20°C, was used to examine trends in high temperature events.[27]

Precipitation

Precipitation data are included in this compendium of physical data as they are generally correlated with discharge levels and in some cases, water temperature. They may also be useful for downscaling projected changes in regional precipitation due to climate variation to the local level, as is available from most climate model outputs. The EC METEOROLOGICAL SERVICES web site was queried for total daily precipitation (mm) for the available years (1961 to 2012) for climate station *Alberni Robertson Creek* (1090230). Missing precipitation data at *Robertson Creek* station were not interpolated or in-filled from other stations, and thus extend only from 1961-2012. Total daily precipitation data are plotted along with Robertson Creek mean air temperature.

Water Temperature

Water temperature data were assembled for three key sites along the migratory route of Somass sockeye, including the Stamp Falls fishway for GCL-bound fish, the Sproat River fishway for Sproat-bound fish, and the lower Somass River at the

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[26] Derivation of the seasonal flux point between warming and cooling "seasons" is described in section Air/Water Temperature Relationships.

[27] Mote et al. (2003) suggest a monthly average air temperature of 20°C to be a dependable upper threshold for identifying suitable salmon habitat.

Papermill Dam site, where both stocks enter the watershed (Figure 2). The resulting datasets were stored in a relational MICROSOFT ACCESS® FRESHWATER ENVIRONMENTAL VARIABLES DATABASE and are available from DFO upon request.[28]

A variety of sources and data types (e.g., instantaneous measures from hand held thermometers, and sub-daily samples from automated thermographs) were assembled for these locations. Electronic records of thermograph readings were received as point temperatures at regular intervals within a given 24-hour period, or as average temperatures of multiple samples across the interval. Sub-daily, interval data ranged from half-hourly, to hourly, to measurements taken every 3, 4, 6, 8, or 12 hours. When multiple sources provided data for the same location and time period, the source covering the longest interval of time with the best temporal resolution was chosen for inclusion in the tables. For data validation purposes, water temperature records were supplemented with data from:

- instantaneous, but long-running and regularly-sampled (approximately weekly) Somass spot temperatures from the CATALYST PAPER CORPORATION (CPC, Port Alberni) as part of ENVIRONMENT CANADA'S ENVIRONMENTAL EFFLUENT MONITORING PROGRAM (EEMP) datasets;
- DFO field surveys and supplemental physical data measures; and
- WATER SURVEY OF CANADA (WSC) hydrographic stations in the Stamp/Somass watershed (stations 08HB009, 08HB010, and 08HB017).

Observed water temperature data can be classified into three categories based on temporal data resolution:

- Class 1: Automated, date-specific data summarized from multiple samples evenly spaced over a 24-hour period;
- Class 2: Daily mean values, derived from automated data summarized from date-specific samples, though of unknown frequency and/or interval; and
- Class 3: Instantaneous and possibly routine date-specific "spot" samples, taken at a specified or unspecified time of day, but most likely during daylight hours, and therefore systematically biased.

Class 1 datasets provide the highest resolution and least potential bias, and are therefore the most appropriate data for statistical use in site-specific air-to-water and inter-site water-to-water temperature relationships. Class 2 and Class 3 data may be used to extend these Class 1 time-series, but only if the data are found to be statistically equivalent, using parametric comparisons tests (e.g., ANOVA, paired t-tests).

The following sections describe the specific water temperature datasets used in this analysis to calibrate and validate regression models for estimation of mean water temperature (MWT) from air-to-water temperature relations at three key locations: Somass River (Papermill Dam); Stamp Falls (fishway); and Sproat Falls (fishway).

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SOMASS RIVER AT THE PAPERMILL DAM SITE

Somass surface water temperatures[29] near the mill have been recorded from 1991-2012 by mill personnel for the EEMP (Larry Cross, CPC, Port Alberni; and Janice Boyd, ENV. CANADA, EEMP unpublished data). These data are collected adjacent to the "lime-rock dock", approximately 1 km up-river from the mouth of the Somass, generally between 10:00 and 16:00 hours. EEMP sampling effort varied considerably between years, and between months within years. In the summer months, water quality samples were taken weekly in recent years and in some years every 3 or 4 days.

Somass water temperature data have been supplemented in recent years with hourly mean water temperatures obtained from data loggers installed at the Papermill Dam site, by DFO (end of August to early November 2000; J. Till, DFO Nanaimo, pers. comm.), and the B.C. CONSERVATION FOUNDATION (2009-2010; K. Pellett & J. Damborg, BCCF, Nanaimo, pers. comm.).

STAMP RIVER FISHWAY

Sub-daily temperature records (sampled every 6 hours) were made available from project-specific thermograph installations at the *Stamp River Falls* fishway (June 2000 - July 2004) by DFO personnel (J. Till and P. Rankin, DFO Nanaimo, pers. comm.). Similar data were collected for a short period (end of August to early November 2000) in the *Somass River* near the CPC mill (J. Till, DFO Nanaimo, pers. comm.). Other sub-daily data for which only daily means are currently available were provided by DFO (Kim Hyatt, Margot Stockwell, unpub. data) for 1993, 1995 and 1996.

Stamp River MWT data have been supplemented recently by hourly mean water temperatures obtained from data loggers installed at Stamp Falls (2009, 2012), in the Stamp above the Sproat confluence (2008-2012) and below the Ash confluence (2009-2012), by personnel at the B.C. CONSERVATION FOUNDATION (K. Pellett & J. Damborg, BCCF, Nanaimo, pers. comm.).

SPROAT RIVER

Sub-daily temperature records (sampled every 6 hours or more) were made available from thermograph installations in Sproat River for discontinuous time-periods in 1996 and between 2000 – 2004 and 2006 (J. Till, DFO Nanaimo, pers. comm.). However, sampling settings on the OPTIC STOWAWAY device were set to record the maximum hourly temperature (instead of the average) for most of July and August 2003, and for all data in 2004 and 2006, rendering these data positively biased.

MWT data for the Sproat watershed have been supplemented recently by hourly mean water temperatures obtained from data loggers installed in Sproat River above the Stamp confluence and at the highway bridge (2009-2012) by the B.C.

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[29] Somass surface water samples also included salinity, pH, and dissolved oxygen (mg/L and % saturation) under the EEM program.

CONSERVATION FOUNDATION (Pellett et al. 2015).

Other high-resolution water temperature data are available from samples collected by the automated DISTRIBUTED CONTROL SYSTEM (DCS) at CPC, at the mill end of an inflow pipe from Sproat Lake, since 1998, but most consistently since June 2003 (Larry Cross, CPC, Port Alberni, pers. comm.). However, due to irregularities in the water temperature time-series associated with the pipeline[30], the DCS data are likely positively biased, and therefore were not used to parameterize the Sproat air/water temperature relationship.

Water Temperature Analyses

Water temperature data cleanup consisted of examining descriptive statistics and graphic output to identify anomalous data and outliers, in conjunction with a review of field notes regarding data logger installation, removal dates and times. All anomalous data were retained in the database but flagged for omission (i.e., OMIT field = YES) from analysis.

All water temperature data sets for the Somass watershed were originally assembled in a Microsoft Excel® spreadsheet[31] grouped by sub-basin, site, year, date, and hour. Times for valid sub-daily water temperature data were rounded to the nearest hour. If multiple observations per hourly interval were recorded, temperature measurements were averaged for the hour. The data records are annotated with source and contact information, including thermograph make, model, and serial number where available, plus recording settings such as the device sampling technique (average, maximum, singular, etc.) and sampling interval in hours. Daily mean water temperature datasets are available in the Microsoft Access® SOCKEYE AND FRESHWATER ENVIRONMENTAL VARIABLES DATABASE (Hyatt and Stiff, DFO unpublished data) and imported into SAS® programs for analysis.

Water temperature data were averaged by site and date. Univariate statistical analyses were used to characterize the site-specific daily MWT time-series for the period of record (i.e., number of observations, central tendency (mean, median, mode, etc.), variation (range, variance, extreme values and outliers), and shape (skewness, kurtosis)).

Somass River data logger readings, made available for intervals in 2009 and 2010 (Pellett et al. 2015) were used in regression procedures to evaluate the presence of sampling bias in weekly spot temperatures provided by CPC.

Select daily MWT data were used with our MAT index to establish site-specific air-to-water temperature regression relations[32], described below.

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[30] CATALYST MILL intake water is pumped from the Stirling Basin in Sproat Lake at a depth of 3 m (or less in summer when the lake level is lower) through a buried pipe for a distance of approximately 6 km to the paper mill in Port Alberni. The pipeline was located on the surface from 1998 to October 9th, 2002, but is currently buried 3 m below ground for most of its length, except at a road crossing near the Port Alberni landfill, and for the last section along a trestle crossing the Somass River (Larry Cross, CATALYST PAPER LTD., Port Alberni, pers. comm.).

[31] Microsoft Excel® spreadsheet SOMASS WATER TEMPERATURES BY SITE DATE HOUR.XLS.

A threshold-exceedance analysis, tallying the decadal mean monthly frequency of dates for which the reconstructed MWT temperature index exceeded 20°C, was used to examine site-specific trends in water temperature conditions during the adult migration period.

Air/Water Temperature Relationships

Various authors have used regression models to illustrate the close relationships that exist between fresh water and air temperatures on hourly, daily, weekly, and seasonal time scales (Hyatt and Stockwell 2003; Pilgrim, Fang and Stefan 1998; Stefan and Preud'homme 1993; Webb and Nobilis 1997). These studies have demonstrated that variations in local air temperature are generally sufficient to explain as much as 80% of the seasonal variations in local daily mean water temperature (MWT), utilizing either linear or nonlinear regression models (Mohseni and Stefan 1999).

LINEAR REGRESSION

Regression relations between air and water temperature are known to be accurate at moderate air temperatures (i.e. 10-20°C) (Mohseni and Stefan 1999). Because mean temperatures in the Somass watershed generally fall within this range during adult sockeye migration, reasonable predictive relationships could be expected for freshwater temperatures as a linear function of regional air temperature, according to the following model:

Equation 7: $T_w = \alpha + \beta * T_a$; where

T_w is the estimated water temperature;

T_a is the air temperature index; and

α is the y-intercept and β is the regression coefficient.

However, due to the effects of freezing at low air temperatures and evaporative cooling at high temperatures (hysteresis[33]), the true air/water temperature relationship does not remain linear at the full range of regional air temperatures, and a linear model will therefore misrepresent site MWT at the both lower and upper temperature extremes, depending on waterbody characteristics. The large surface area and volume of lakes and large rivers has a major influence on the differential rates of seasonal heat exchange (Hyatt and Stockwell 2003). Thus, streams and creeks located upstream of major water bodies may exhibit little or no hysteresis effects, due to their small surface area and continuous flushing activity.

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[32] It is also possible to derive site-to-site water temperature relations between a reference site (which has a well-established air-to-water temperature relationship) and secondary watershed sites of interest.

[33] Hysteresis: the heat storage properties of water. Hysteresis is a measure of the seasonal effect of the differential rates of heat exchange between air and water as the spring-to-summer period warms up and the fall-to-winter period cools down (Wetzel 1975). The observed pattern of hysteresis is related to the complex physics of air-water heat exchange processes. These involve evaporative cooling of the lake in the late summer-to-fall, thermal de-stratification in the fall-to-winter; rapid, wind-induced, mixing of surface and deep waters through the winter, and initiation of thermal stratification and evaporative cooling once again in the spring-to-summer season.

One method of accounting for hysteresis is to utilize separate linear functions for the warming and cooling periods of the year, by partitioning the dataset into seasonal components (*spring-summer*, *summer-fall* and (optionally) *winter*), in order to obtain more meaningful predictive relationships (e.g., the "broken stick" model - Hyatt and Stockwell 2003).

To do this, the warming and cooling "seasons" must first be delineated by determining the upper thermal "turn-around point" (Mohseni, Stefan and Erickson 1998) for each water temperature site. The point of seasonal transition was set to the week of maximum mean daily air temperatures – which usually also corresponds to the maximum mean daily water temperatures. Ignoring the *winter* season (for which air/water temperature relations are poor), the weekly period associated with the minimum mean air temperature defines the starting point of the warming season (and the ending point of the cooling season), and the period associated with the maximum mean air temperature indicates the ending of the warming season (and the starting point of the cooling season) – most often in early-to-mid-August in coastal B.C. The day-of-year (DoY) of the summer seasonal transition is approximated by multiplying the week value by seven days (e.g., week 30 → DoY 210), and this value is used to delineate all time-series into either warming or cooling seasons.

The existence of hysteresis in a waterbody, and the resulting need to use separate warming and cooling season regressions models to describe air/water temperature relations at a particular site, can be evaluated by testing whether an additional categorical "season" predictor in the linear air-to-water model is a significant effect (signifying different seasonal model intercepts) and/or whether there is a significant interaction effect with air temperature, indicating significant differences in seasonal model slopes (i.e., $P < 0.05$ for the Type III model sum of squares (SAS 2008).

Limitations inherent in the linear "broken stick" method include poor estimation of *winter* temperatures due to a lack of relationship between air and water temperatures at freezing levels; and possible temporal discontinuities at the juncture between warming (*spring-summer*) and cooling (*summer-fall*) seasons due to significant differences in the coefficients of the seasonal relations. These limitations may be problematic where examination of environmental influences on a given salmon, life-history event requires application of continuous, multi-season analysis.

NONLINEAR (LOGISTIC) REGRESSION

An alternative approach involves fitting a nonlinear logistic curve[34] to the air/water temperature data (Mohseni, Stefan and Erickson 1998):

Equation 8: $T_w = \mu + (\alpha - \mu) / (1 + e^{\gamma(\beta - T_a)})$; where

T_w is the estimated water temperature;

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[34] Assuming the variability of values follows a Gaussian distribution, a multivariate secant method may be used to estimate the four parameters (Mohseni, Stefan, and Erickson 1998).

T_a is the measured air temperature index;

α is the estimated maximum water temperature;

μ is the estimated minimum water temperature;

γ is a measure of the steepest slope of the function; and

β represents the air temperature at the inflection point.

When the function is derived from a comprehensive range of site air and water temperatures, and hysteresis is not a factor (small or rapidly flushing streams), the logistic regression method can integrate the full cycle of the seasons into a single mathematical relationship.

Again, however, waterbody size, flow rates, and other characteristics can influence the form and fit of the logistic equation. The most appropriate form of the logistic model may depend on the minimum temperature range (parameter μ) for the watershed. Where water bodies freeze, minimum water temperatures can reach 0°C; thus, the parameter μ, should be set to zero (i.e., removed from the function – Mohseni and Stefan 1999), as in Equation *9* (other parameters are defined as in Equation *8*):

Equation 9: $T_w = \alpha \,/\, (1 + e^{\gamma(\beta - T_a)})$

For the large lakes and rivers in the coastal Somass ecosystem, which do not freeze in winter, minimum water temperature remain above zero (i.e., $\mu \neq 0$), and parameter μ is estimated from the data, as in Equation *8* above.

To detect hysteresis effects in the nonlinear model, goodness-of-fit is assessed from the *Nash-Sutcliffe Coefficient* (NSC), calculated as (Mohseni and Stefan 1999):

Equation 10: $NSC = 1 - (\Sigma\,(T_{sim} - T_{obs})^2 \,/\, \Sigma\,(TBAR_{obs} - T_{obs})^2)$; *where*

T_{sim} = estimated water temperature;

T_{obs} = observed water temperature; and

$TBAR_{obs}$ = mean observed water temperature.

The degree of hysteresis in a water body is assessed from a comparison of the NSC value for the all-season model versus the (averaged) NSC values for the separate warming and cooling season models (Mohseni, Stefan, and Erickson 1998):

Equation 11: $Hysteresis = [(NSC_w + NSC_c) \,/\, 2 - NSC_{all}] \geq 0.01$; *where*

NSC_w = NSC for warming season;

NSC_c = NSC for cooling season;

NSC_{all} = NSC for all seasons combined;

If the averaged seasonal NSC is larger (i.e., $\geq NSC_{all} + 0.01$) than the NSC of the one function fit to the entire dataset, hysteresis exists. The presence of hysteresis indicates that the warming and cooling season equations are better suited for predictive purposes than the single function derived from the entire time-series.

Employing two nonlinear equations to model a water body's temperature may result in a discontinuous "step" event in the daily time-series at the seasonal transition date where the two equations "meet" (similar to the linear "broken stick" method). This is largely due to insufficient data distributed in the upper thermal range for both seasonal models. The step effect may be reduced by selecting calibration data that contain representative observations at the upper end of the temperature range for both warming and cooling seasons, or by "tuning" the date of the seasonal transition to distribute available observations in the high temperature range more evenly between seasons. In extreme cases (where modeled seasonal water temperatures differ by 1°C or more at the transitional date), the average of the seasonal model alpha parameters was applied to both models to smooth the transition between the last date of the warming season, and the first date of the subsequent cooling season.

Water Temperature Time-Series Reconstruction

MODEL CALIBRATION

Linear and logistic regression relations described above were developed using site-specific, daily-mean, water temperatures (MWTs) from the sub-daily (Class 1) data set for *Stamp Falls* and *Sproat River* as a function of the regional air temperature index (7d centered ROBERTSON CREEK STANDARD MAT). Class 3 water temperature data, sampled weekly at the "lime-rock dock" of the CATALYST paper mill, were used to model air/water temperature relations at the *Somass River* location. These data represent the only main-stem Somass water temperature time-series consistently recorded (1991-present).

Model calibration data were selected based on examination of annual air and water temperature time-series and correlation plots. A minimum of 5 years of representative data including sufficient observations at the upper end of the temperature range for both warming and cooling seasons were obtained from source datasets partitioned as follows:

Reference Site	Calibration Years	Validation Years
Somass River (Papermill)	1991, 2000-2001, 2003-2004, 2009-2010	1992-1999, 2002, 2005-2008, 2011, 2012
Stamp River Falls	2000-2004	1993, 1995, 1996, 2009 - 2012
Sproat River Falls	1996, 2000, 2002, 2009-2010	2001, 2003, 2012

To determine whether seasonally-distinct regression relations were required, the air/water temperature data for each water body were checked for hysteresis. To detect hysteresis, separate functions were fitted to the air and water temperature data in each of the warming and cooling seasons[35].

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[35] Since all Somass reference sites fall within the lower altitudes of the pluvial coastal climate zone with mean minimum daily winter temperatures above 0°C, parameter μ was incorporated, as in Equation 8.

The warming and cooling seasons were first distinguished from each other by determining the seasonal temperature "turn-around point" (the timing of the winter season turn-around point was not required for the purpose of this analysis)[36]. The seasonal transition dates were obtained by plotting the weekly mean of daily water temperatures as a function of the weekly mean of daily air temperatures, and connecting the points chronologically. The week associated with the maximum mean air temperature, indicating the ending of the warming season (and the starting point of the cooling season) was converted to day-of-year to pinpoint the seasonal turn-around date. Since the same regional air temperature index is used for all Somass water temperature reference sites, the same seasonal turn-around point applied to all locations, and for both linear and logistic models.

Site-specific hysteresis effects were then assessed as described above using all-year, all-season data for both linear and logistic models. If hysteresis was detected in either case, linear and logistic models were then fitted to the all-year data for each of the warming and cooling seasons separately.

MODEL VALIDATION

Site-specific linear and nonlinear air/water regression parameter estimates were tested for statistical significance, and applied to the ROBERTSON CREEK STANDARD air temperature index to estimate reference site daily MWT for the period of record of air temperature data. Modeled MWTs for the validation dataset were correlated with observed reference site water temperature data graphically and statistically as a measure of goodness-of-fit. The all-year Pearson and Spearman correlations for the validation years were compared between model types to determine whether linear or logistic outputs best simulated observed MWTs at each site.

Time Trend and Exceedance Analyses

AIR TEMPERATURE

Historic mean daily air temperature data (based on ROBERTSON CREEK STANDARD index, 1918-2012) were summarized by year to obtain the mean value during the summer months (July-September), and plotted to review the long-term time trend in regional air temperature conditions during the migratory period for Somass Sockeye.

Monthly mean air temperatures of 20°C are considered an upper threshold for salmonid life history stages (Mote et al. 2003). The air temperature index was analyzed for the frequency of dates in each year and month for which the mean daily air temperature exceeded this threshold value, and summarized by decade as a trend indicator.

WATER TEMPERATURE

Reconstructed daily mean temperature data were summarized by site and year to determine mean values during the summer months (July-September), and plotted to review the long-term time trend in site-specific water temperature conditions during the migratory period.

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[36] For linear models, an additional "winter" season was defined for the linear analysis (November 25th to March 10th), encompassing the cold-weather months when changes in air temperature are not reflected in changes in water temperature due to hysteresis effects at low temperature extremes.

Water temperatures above 18°C are considered stressful for migrating adult sockeye salmon over extended time periods (McCullough et al. 2001), though stock-specific variation in tolerances based on geography and site exist. For example, Okanagan sockeye appear to have some tolerance for water temperatures in excess of 20°C (Hyatt and Stockwell 2003). Similarly, Sproat sockeye may be routinely observed migrating through a short segment of the Sproat River, at temperatures in excess of 20°C or more, while GCL-bound fish generally migrate at 19°C or less (Pellett et al. 2015). Site-specific water temperature thresholds were used (19°C in the Stamp River; 20°C in the Sproat River) in conjunction with modeled water temperature estimates to determine the frequency of dates in each year and month for which mean daily water temperature exceeded threshold values that were clearly stressful (summarized by site and decade).

In addition, the frequency of annual periods in which water temperature continuously exceeded site-specific thresholds, and the mean duration (days) of these periods were derived for each year. These data were summarized by site and decade as indices of trends in the frequency and duration of continuous periods of stressful temperature conditions.

RIVER DISCHARGE

For discharge-exceedance analyses, both "low flow" and "high flow" dates are of interest, since, conceivably, either may influence upstream migration (e.g. see Pellett et al. 2015 for details). "Low flows" correspond to dates for which the daily flow rate was less than a threshold value, defined in this study as the 25th percentile of observed Jun-Sep discharge (i.e., at Stamp Falls 1914-1978: ~24 cms; at Sproat Falls 1913-2012: ~5 cms). Discharge data were analyzed for the frequency of dates in each year and month for which mean daily discharge did *not* exceed the lower threshold value, and summarized by decade. In addition, the frequency of annual periods in which flow levels continuously remained below the threshold, and the mean duration (days) of these periods, were derived for each year. These data were summarized by decade to review trends in the frequency and duration of continuous periods of potential barriers to upstream migration.

A similar exceedance analysis was performed for "high flows" to tally the frequency and duration of periods for which discharge exceeded the 75th percentile of observed historic Jun-Sep flows (corresponding to ~60 cms at Stamp Falls, and ~22 cms at Sproat Falls), to review decadal trends in "flood" conditions that might impede upstream migration.

Mean daily discharge at Sproat and Stamp Falls (observed + estimated) was calculated for each year for the Sockeye migratory period and plotted to examine long-term trends (1914-2012) in water conditions. Regression statistics were reviewed for significance of the trend for the duration of the time-series.

Migration, Temperature and Discharge

Daily mean water temperature and discharge time-series were merged with daily migration rate data for co-variation analyses, using lagged dates where appropriate. To match migration data obtained at the GCL fish-way with environmental data at the Stamp Falls fish-way, 2 days were subtracted from the migration data; for lower Somass conditions, 5 days were subtracted from GCL migration data, and 3 days from Sproat migration data. To match Sproat migrants with Sproat River conditions, no lags were required since all data were collected near the Sproat Falls fish-way. Since limitations due to combined temperature and flow conditions for GCL-bound Sockeye were more likely to be a factor at the Stamp Falls fish-way than in the lower Somass, the Stamp Falls site was selected for environmental co-variation and exceedance analyses (as opposed to the Papermill site)[37].

To characterize the temperature and discharge conditions during historical stock migration, frequency distributions of observed active migration dates (i.e., filtered for non-zero migration rates) at varying levels of temperature, discharge, and both temperature and discharge, were generated. By tallying the number of dates in the historical dataset at which any migratory activity occurred, these plots indicate the general distribution of temperature and discharge conditions that were available during the migratory period.

A similar frequency distribution of active migration dates, weighted by the daily migration rate, was generated to indicate how much migration occurred at a given temperature, discharge, or temperature-and-discharge combination. In contrast to the simple distribution of dates of migration, these plots indicate which temperature and discharge conditions are associated with highest migration rates (i.e., presumably most favourable to salmon migration), and, by extension, the thermal and hydrological limits (if any) that differentiate high versus low rates of migration.

Environmental "limits" derived subjectively from the weighted frequency distribution plots were used to set threshold values for calculation of daily deviations in the modeled water temperature and discharge time-series, and combined with deviations in daily Sockeye migration rate on annual anomaly plots to examine the pattern of daily variation in each time-series in relation to each other.

The anomaly plot "zero-line", or threshold, for migration data was set to the 75th percentile of the historical daily migration rate (0.79% for Great Central Lake sockeye; 1.07% for Sproat Lake sockeye). These stock-specific migration threshold values were subtracted from the historical daily migration rates to derive the anomaly for daily migration. In this way, the 75th percentile migration rate is used to define whether a particular daily migration rate value is "significant" or "high" (positive) versus "insignificant" (negative) in relation to the zero-line.

For comparability, the water temperature zero-line threshold was set to 20°C for both GCL- and Sproat-bound fish, based on approximate thermal barrier levels for entry by migrating Sockeye into the lower Somass River from Alberni Inlet (Pellett et al.

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[37] Alternatively, to incorporate the possible effects of thermal barriers to migration in the lower Somass with potential flow barriers at Stamp Falls, a three-day backward lag, applied to Somass water temperature data (i.e., subtract three days) before merging with Stamp Falls sockeye counts and discharge, could be used to account for fish travel time between the two sites.

2015) and, as suggested here, by stock-specific contour plots of migration versus temperature and discharge.

Low flows at the fish-ways associated with the low end of significant migration were identified from weighted frequency plots of migration activity, described above. A discharge rate of 10 cms in the Sproat River was selected as the flow threshold for Sproat-bound fish, and 40 cms in the Stamp River was selected for GCL-bound fish. The difference between these thresholds and the site-specific daily mean temperature and discharge estimates were plotted as anomalies on a common secondary y-axis (discharge was scaled by 0.15 to fit the axis) to review the co-variant pattern of migration against environmental changes with migration rate anomalies on the primary y-axis.

RESULTS

MIGRATION DATA

Great Central Lake Sockeye

Great Central Lake sockeye migration data (total of adults plus jacks), summarized by year, indicate that migration typically commences in May or early June, reaches 50% (TT50%) by mid-July, and terminates in late October or November (Figure 3), though in 2012, characterized by both favourable flow and temperature conditions until after July 9th (see 2012 panel plots in Appendices A and B), migration was complete by September 3rd (Table 1). Non-zero migrant counts average approximately 1,500 ± 3,000 fish per day; maximum daily counts may surpass 30,000 fish. 95% of daily counts are less than 6,000 fish, and the median estimate for the all-year dataset is 561 fish per day (Table 1).

The corresponding all-year mean daily migration rate hovers below 1%, with peak daily rates typically in the range of 7-10%, though approximately 17% of the annual escapement occurred on one day in 1979 (Table 1).

Annual time-series of Great Central Lake sockeye daily migration rates (%) are plotted in Appendix A, along with mean and maximum daily migration rates across all years 1976-2012. Annual plots are organized in a multi-panel format for inter-annual comparison of timing and migration events.

Sproat Lake Sockeye

Sproat Lake sockeye migration (adults plus jacks; 1974-2012) typically commences in May or early June, but started as early as April 22 in 2002 (Table 2). TT50% occurs in mid-July, but may be a few days earlier than GCL-bound fish (Figure 4). Migration is largely complete by late October or November, though in some years (1995, 2007, 2008, 2012), migration finished by early September (Table 2). During the years 1974-1979, migration also terminated early (as early as August 21st in 1976), and the active migration period was less than 100 days. Migration timing appears to have expanded or shifted to later dates since the 1980's (Table 2).

Non-zero migrant counts average approximately 1,300 ± 2,200 fish per day; maximum daily counts have surpassed 25,000 fish. 95% of daily counts are less than 6,000 fish, and the median estimate for the all-year dataset is 553 fish per day.

The corresponding all-year mean daily migration rate hovers well below 1%, with peak daily rates typically in the range of 4-6%. A maximum daily rate of 12% of the total escapement occurred in 1979 and 2009 (Table 2).

Annual time-series of Sproat Lake sockeye daily migration rates (%), organized in a multi-panel format for inter-annual comparison of timing and migration events, are plotted in Appendix A, along with mean and maximum daily migration rates across all years 1974-2012.

DISCHARGE DATA

Observed daily mean discharge data obtained from WSC archives are summarized for all years and all months (Table 3, Table 5, Table 7), and for the peak migration months (July-September) for the decades since installation of a re-engineered Great Central Lake Dam in 1957 (Table 4, Table 6, Table 8). Historically, Somass River discharge has varied considerably. Typical flow rates range from 92.6 m^3/s (3,270 cfs) to 160 m^3/s (5,660 cfs), although flows as low as 21.6 m^3/s (764 cfs) have been recorded. A peak flow of 1,150 m^3/s (40,600 cfs) was recorded January 15, 1961 due to a major winter rain-on-snow event.

Mean, median and modal statistics indicate that, at moderate to high flow levels, the Stamp system contributes about 60-70% of the Somass daily discharge, and the Sproat system accounts for about 25-30%. At very low flow rates (< 25 cms in the Somass), water sources other than the Stamp and Sproat systems (e.g. Elsie Lake and Ash River) may contribute as much as 25% of the lower Somass flow rates.

Trends in Observed Discharge

Lowest daily flows occur in mid-to-late August, during the principal Sockeye migration period (Figure 5). Prior to 1957, extreme low flows (< 5th percentile) in the Stamp River dipped below 10 cms with minimum flows of 2.5 cms; since dam construction, the minimum flow has been 18 cms, and the 5th percentile is closer to 25 cms (Table 4). While median summer flows have also increased (from ~23 cms to ~38 cms), maximum flows have remained about the same (<225 cms). The long-term trend suggests a 3 cms per decade increase in Stamp flow levels (Figure 6); however, it must be noted that the observational time-series terminates in the late 1970's, which were largely characterized by cool, wet weather in the Pacific Northwest[38].

A comparison of daily discharge in the largely unregulated Sproat River before and after the late 1950's indicates that minimum to median summer flow levels have diminished by 25-30%, with historical mean flows of 12.9 ± 9.6 cms reduced to 9.8 ± 9.8 cms in recent decades, and a long-term trend of -0.5 cms per decade (Figure 7). Extreme low flows (<5th percentile) have dropped from ~3 cms to 1.3 cms, indicating a higher proportion of dates in the migration period were characterized by low water levels (Table 8). The weakly negative trend for Sproat River levels does not repudiate the influence of regional cool, wet weather on flows in the Stamp/Somass in the 1970's, but shows that conditions since then have been predominantly characterized by drier warm-phase ocean climatology.

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[38] The late 1960's and 1970's were characterized by cool-phase PDO and cool- or neutral-phase ENSO conditions up to 1977 (Mantua and Hare 2002).

Estimating Missing Somass River Discharge

Missing daily flow data in the lower Somass were estimated from historical Sproat data based on linear and non-linear relationships. Cross-correlation analysis based on calibration data sub-sampled from 10% of the available data indicated high non-parametric Spearman correlations between discharge at the Sproat and Somass locations based on all-season data ($r_S = 0.96$, $P < .0001$, $n = 1{,}477$; Table 9) and for data filtered for summer months (July-August-September; $r_S = 0.87$, $P < .0001$, $n = 384$; Table 10). However, the linear regression analysis also indicated a significant lack of fit in the error term (Figure 8, Figure 9), evidence of heteroscedastic non-linearity in the residuals.

The non-linear nature of the relationship was illustrated by the log-log transform of the two discharge datasets (Figure 10); the Somass maintains a steady minimum flow of ~20 cms (since 1960) at low water levels in the Sproat system, while at high water levels, the Somass increases in volume exponentially relative to Sproat. The log transformation of the data did not however, improve the fit relative to the linear analysis, as indicated by the still significant lack of fit term ($P < .0001$) (Figure 11).

The parabolic curvilinear relationship was then fit to the data (Figure 12; Figure 13):

Equation 12: *Somass (cms)* $= 18.7 + 2.6x + 0.0014x^2$; where x = *Sproat discharge (cms)*

Spearman correlation analysis comparing observed and estimated Somass discharge rates indicated an improved fit: $r_S = 0.95$ ($P < .0001$, $n = 16{,}238$). Annual plots of observed and estimated daily Somass flows (Figure 14) indicated that the curvilinear model reasonably estimates variation in observed Somass flows in the summer months for most years. The model tends to under-estimate some extreme high mid-summer Somass flows (*c.f.* 1978, 1979, 1997, 2001) likely due to the localized nature of precipitation events in contrasting watershed basin sizes – rainfall events occurring in the Stamp/Somass watershed may have bypassed the Sproat watershed, such that associated flows in each system are occasionally uncorrelated.

Estimating Missing Stamp River Discharge

Missing daily flow data in the Stamp River were estimated based on Somass-to-Stamp relations, which were almost linear for the years 1960-1978. Though linear regression yielded the strongest Somass-to-Stamp discharge relation ($r^2 = 0.95$, $P < .0001$, $n = 634$; Figure 21), a significant lack-of-fit component (Figure 22) suggested a nonlinear approach based on a power equation ($r^2 = 0.93$; Figure 23, Figure 24) to estimate Stamp flows up to 2002. A quadratic curvilinear relationship did not improve the Somass-to-Stamp fit (Figure 25, Figure 26).

Simple linear and log equations demonstrated strong lack-of-fit for Sproat-to-Stamp relations, due again to the nonlinear relation for the contrasting daily discharge volumes between Sproat and the larger Stamp system (Figure 15 - Figure 18). A quadratic function provided the best-fit Sproat-to-Stamp relation to infill missing

Stamp discharge values since 2002 (Figure 19, Figure 20).

The transfer function sequence to estimate missing Stamp flows then becomes:

Equation 13: $Stamp = 1.159 * Somass^{0.882}$; *for 1957-2002*

Equation 14: $Stamp = 21.3 + 1.51*Sproat + 0.0008*Sproat^2$; *for 1913-1956, 2002-2013*

Correlation between observed and estimated Stamp flows via this method yielded an improved Spearman coefficient of $r_S = 0.96$ ($P < .0001$, $n = 6{,}909$), though sample plots comparing these variates indicated, again, that parametric methods tend to underestimate upper extremes (e.g., 1957, 1975, 1978, etc.; Figure 27). This was most evident in years where Stamp discharge must be estimated from Sproat data (i.e., 2002-present), and therefore caution is advised in interpreting the weakly positive time trend in mean summer discharge levels of 0.6 cms increase per year ($r^2 = .007$, $P < .001$; Figure 28), as the last ten years of the combined observed and estimated time-series may be biased low. The inherent limitations of using Sproat River as the reference discharge station for the Somass basin underscore the need to install and maintain active water flow/level data loggers in the Stamp/Somass watershed.

WATER TEMPERATURE DATA

All observed daily water temp time-series are available on CD-ROM in the Microsoft Access® FRESHWATER ENVIRONMENTAL VARIABLES DATABASE (Hyatt and Stiff, DFO unpublished data). High resolution Class 1 daily mean water temperature (MWT) datasets were used where available and sufficient to characterize the thermal range for derivation of air/water temperature relationships, and supplemented with lower resolution data if necessary.

Somass River

Weekly spot temperature data (Class 3) provided by the ENVIRONMENTAL EFFLUENT MONITORING PROGRAM (Source: CPC in Port Alberni) were used to derive Somass air/water temperature relations, based on the length of this time-series (1991-present), as well as the limited availability of Class 1 data logger observations (partial time-series for 2009-2010 were made available by BCCF). Somass EEMP data (Somass River at Papermill Dam) are summarized in Table 11 and the time-series is plotted in Figure 29. Thermograph plots by year (Figure 32) and all-year mean daily values ± two standard deviations (Figure 33) indicate maximum temperatures occur in early August, but may surpass 20°C at any time between mid-June and mid-September. Mean and median summer month temperatures indicate that the warmest conditions during migration in this time-series were found in 1998, 2003, 2004, and 2009. Daily MWTs exceeded 20°C for 50% of the time from July to September for some of these years (1998, 2003 and 2005). Coolest conditions were found in 1999 and 2012.

Stamp River

Calibration data for the Stamp River reference site were obtained from data logger time-series for the years 2000-2004 (Figure 30). Water temperatures for this dataset for the summer months are summarized in Table 13. As in the Somass time-series downstream, peak temperatures in the Stamp occur in early August but may range from July to September (Figure 34, Figure 35). Mean temperatures ranged from 18-20°C in the summer months, and averaged about 0.5°C less than Somass River water temperatures over the same time period.

Sproat River

Class 1 Sproat River reference site data were obtained from data logger time-series for the years 1996 and 2000-2003 (Figure 31); summer month water temperatures are summarized in Table 13. Peak temperatures in Sproat River occur in early August but may range from early June to late September (Figure 36). Daily MWTs for this time-series may exceed 20°C from early July to September (Figure 37). Maximum daily MWTs exceeded 22°C in all years, and exceeded 25°C in 2003 and 2009. 50% of the active migration period from July-September is characterized by temperatures of 21°C or more (Table 13).

Inter-Site Water Temperature Relationships

Class 1 daily mean water temperatures for the Somass River from BCCF data loggers installed near the Papermill Dam (2009-2010) were compared with CPC Class 3 spot temperatures using simple linear regression analysis, to check for sampling bias in the CATALYST dataset (Figure 38). Neither was the intercept significantly different from 0, nor the slope significantly different from 1, indicating a virtual one-to-one relationship between the independent temperature dataset and CPC EEMP data[39]. These findings indicate that the EEMP time-series provides a relatively unbiased representation of Somass River water temperatures.

Observed Stamp River data (source: DFO data logger readings 2000-2004) were compared with the Somass CPC dataset to evaluate temperature differences between upstream and downstream sites (Figure 41). Assuming no bias in the observed Somass data (based on the Somass multi-site analysis above), the highly correlated linear relationship between Somass and Stamp indicates that the Somass is a maximum of 0.5°C warmer than the Stamp at the range of temperatures found during sockeye migration:

Equation 15: $\text{Somass MWT } (^\circ C) = 0.68 + 0.98 * \text{Stamp MWT } (^\circ C); (r = 0.99, n = 221)$

WATER TEMPERATURE TIME-SERIES RECONSTRUCTION

Seasonal Turn-Around Point

The mid-year seasonal turn-around point for all reference sites is in week 30 – approximately July 29th – based on maximum mean weekly air temperatures at the Robertson Creek meteorological station (Figure 40). The “warming season” therefore extends from April 1 to July 29th, followed by the “cooling season” from day 211-329, i.e., July 30th – November 25th. (The “winter” seasonal turn-around point is January 1st, but data between late November and early April are not used in this analysis.)

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[39] $MWT_{CPC} = 0.28 + 1.000 * MWT_{BCCF}$ (n=45, r=0.99, P<.0001)

Multi-Day Air Temperature Index

The multi-day Robertson Creek Standard air temperature index that best correlated with all-year daily mean water temperature was identified as the 7-day centered moving average air temperature index (7d-CMAT). The 7d-CMAT scored the highest correlation for Somass water temperatures and second highest with Stamp and Sproat water temperatures, relative to the 3d-, 5d-, 10d-, and simple daily MAT air temperature indices (Figure 41). Though the 10d-CMAT had a slightly improved r^2 (and smaller AICc), the degree of improvement in correlation for the 10-day correlation relative to the 7d-CMAT was minimal, and overall, the 7D-MAT provides the best trade-off between maximizing correlation and minimizing the effects of multi-day averaging on predictive power at longer period lengths. Thus, the ROBERTSON CREEK STANDARD 7d-MAT was used for subsequent air/water temperature analyses.

Model Calibration and Validation

Logistic and linear air/water temperature models were parameterized using a subset of the available data for calibration, and tested for goodness-of-fit with the remaining years for model validation. Calibration and validation data years, and the number of observations available for analyses by season, are identified for the three watershed reference sites: Somass River (Table 14), Stamp River (Table 15), and Sproat River (Table 16).

Hysteresis at each site was evaluated by comparing Nash-Sutcliffe coefficients (NSC) for all-season logistic models fit to the calibration data against the average NSC for seasonal models. Hysteresis was detected at all sites, indicating that the site-specific air/water temperature relationships were best modeled using separate seasonal models (Somass: Figure 42; Stamp: Figure 43; Sproat: Figure 44). Seasonal model parameters, 95% confidence limits, and NSC goodness-of-fit coefficients are listed for Somass River (Table 17), Stamp River (Table 18), and Sproat River (Table 19).

Linear regression model output for seasonal air/water temperature relationships and calibration data are provided in Table 20 (Somass River daily spot water temperatures), Table 21 (Stamp daily MWT) and Table 22 (Sproat daily MWT). Type III sum of squares for a season effect and a season/air temperature interaction effect are highly significant in all three cases, indicating again, that hysteresis exists and seasonal models provide the best fit to the data (Figure 45).

Predictive estimates of daily mean water temperature were generated for each site, model type and season for the extent of the air temperature record. Correlation analyses between observed and predicted daily MWT values for the validation years were used to compare the predictive skill of logistic versus linear models. Season-specific Pearson (least squares) and Spearman (rank) correlation coefficients for the validation data are contrasted in Table 23 (Somass River daily spot water temperatures), Table 24 (Stamp daily MWT) and Table 25 (Sproat daily MWT). Validation data correlations indicate minor but insignificant improvement of logistic models over linear models for estimating daily mean water temperatures. As the nonlinear model has a predictive advantage at temperature extremes, the seasonal logistic model parameters were selected as the best estimators of daily mean water temperature at each site, and were used to reconstruct historical daily water temperature estimates for the period of available air temperature data. A subset of the validation data years with observed and modeled MWT output, along with daily MAT and the 7-d MAT index, are plotted in Figure 46 - Figure 51.

Trends in Air and Water Temperature

Average summer (July-September) air temperatures based on the regional air temperature index has been increasing since 1920 at a rate of about 0.18°C per decade ($b = 0.018$; $r = 0.16$, $P < .0001$, $n = 8{,}767$; Figure 52 (top)). Since estimated water temperatures are based on this index, it is not surprising that Stamp and Sproat river temperatures are also trending upwards.

Mean Stamp River water temperature for July-September (estimated from seasonal logistic regression model relationships with the regional air temperature index) has been trending in a slightly positive direction since 1920 ($b = 0.009$; $r = 0.17$, $P < .0001$, $n = 8{,}767$; Figure 52 (middle)), suggesting a marginal temperature increase of ~0.1°C per decade. Restricted to the years of available GCL migration data (1975-2012), the warming trend was about double, i.e., ~0.2°C per decade ($b = 0.02$; $r = 0.17$, $P < .0001$, $n = 3{,}530$).

Similarly, estimated Sproat River mean summer water temperatures have been incrementing since the 1920s at ~0.1°C per decade, though baseline temperatures have been 2-3°C warmer than Stamp ($b = 0.011$; $r = 0.18$, $P < .0001$, $n = 8{,}771$; Figure 52 (bottom)).

MIGRATION IN RELATION TO TEMPERATURE AND DISCHARGE

Great Central Lake Sockeye

A frequency analysis of dates of migration through Stamp Falls indicated that ~70% of upstream migration activity occurred above 18°C, with more than half occurring at 18-19°C (Figure 53) and flows of 20-50 cms (Figure 55). The same frequency analysis, weighted by the daily migration rate (%), indicated that the highest daily migration rates (>1% per day (~80th percentile)) occurred at slightly lower water temperatures: ~16-18°C (Figure 54); and higher discharge levels: 40+ cms, with maximum daily migration rates at >60 cms (Figure 56).

3-D and contour plots of daily migration rate at discharge and temperature combinations (omitting infrequent cells, where $n < 5$) reflect a "preferred migration zone" around 16-18°C and 60-70 cms (Figure 57).

A subjective review of migration anomaly plots incorporating zero-lines for temperature (19°C) and discharge (24 cms) based on the above findings (Appendix B) indicated that daily mean water temperatures of 19-20°C constituted a critical threshold between low and high migration rates for GCL-bound sockeye in most years. With few exceptions (e.g., 1977, 2005), water temperatures exceeding this threshold were associated with reduced migration, especially during extended low flow periods (e.g., 1981, 1985-1987, 1990-1996, 1998, 2002, 2004, 2009). In other years, a flow interaction effect was apparent, in which significant migration appears to have been enabled despite higher temperatures via high flows (e.g., 1979, 1991, 1997, 2000, 2007, 2008, 2010, 2012).

In the absence of a high temperature effect, high Stamp River flows (>90th percentile) appeared to have a variable influence on migration rates – in some years, flows exceeding 80-90 cms (not shown) appeared to be associated with stop migration events (e.g., 1978, 1997). In other cases, high flows appeared to have a stimulus effect, corresponding to start migration events *as high flows fall back to the threshold level* (e.g., 1979, 1983, 1991. 1997). High flows are only rarely associated with sustained high migration rates (e.g., 1999) unless coincident with the tail-end of the run (1978, 1979, 1991). These findings indicate that although intermittent high Stamp River discharge levels did not exert a consistently negative impact on GCL-bound Sockeye migration, Stamp discharge levels greater than 80-90 cms may be a deterrent to migration due to physical barrier(s) or the energetic costs of swimming against the flow.

Sproat Sockeye

For Sproat-bound sockeye, a high proportion (~85%) of migration activity occurred when Sproat River temperatures exceeded 18°C, with half of migration dates at temperatures in excess of 20°C (Figure 58). However, highest daily migration rates (>1%, ~75th percentile) are associated with temperatures of 17-21°C (Figure 59).

About 50% of migration activity fell on dates associated with Sproat River discharge less than or equal to 10 cms (Figure 60), with the highest proportion of migration activity occurring at less than 5 cms (~30%). However, "significant" daily migration rates (greater than 1%) are generally characterized by flow levels of at least 10 cms, with the highest rates of migration occurring at 32-36 cms (Figure 61).

Contour plots of daily migration rate versus discharge and temperature (omitting infrequent cells, where n < 5) reflect a range of "preferred migration zones" (Figure 62). Maximum migration rates were found at 18°C at lower discharge levels (12-22 cms), and at 19°C and higher at discharge rates above 20 cms, indicating some tolerance for higher temperatures (e.g., 21-23°C) at discharge levels of 24 cms or more.

Review of anomaly plots with zero-lines for temperature and discharge based on 20°C and 10 cms thresholds (Appendix C) indicates that daily mean water temperatures near 21°C constitute a critical threshold between low and high migration rates for Sproat sockeye in most years, especially during extended low flow periods (e.g., 1985, 1992, 2009). High temperatures are associated with reduced migration in many years (e.g., 1981, 1982, 1987, 2009; with some notable exceptions, e.g., 1977, 1978). In other years, a flow interaction effect is apparent, in which significant migration appears to be enabled via high flows, despite higher temperatures (e.g., 1974, 1975, 1979, 1983, 1991, 1993, 1994, 2008, 2010). Peak Sproat River flows (>33 cms – not shown) do not appear to have a negative impact during peak migration periods (July-August) (e.g., 1977, 1997, 1999, 2012) unless coincident with the tail-end of the run (1975, 1979, 1991).

Thus, water levels (perhaps in combination with the shorter migration distance to cooler waters at depth in Sproat Lake) appear to be a key factor in the ability of Sproat Sockeye to migrate at water temperature levels above typical thermal thresholds of ~20°C. During low flows, Sproat migration rates were still sensitive to higher water temperatures at the 18-20°C threshold, but maximum migration rates were possible at 21-23°C at flows of 24-30 cms (Figure 62). If above average flows are key to migration success as Sproat water temperatures continue to rise (Figure 52), then the long-term decline in Sproat River summer flow levels (currently averaging ~10 cms; Figure 7) may present challenges to the sustainability of this stock.

Air Temperature Exceedance Analyses

A frequency analysis of observed and estimated daily mean air temperature indicates that the cumulative total number of $POT_{>20°C}$ dates per year has steadily risen in the Stamp-Somass watershed over the past century, averaging 19 days per year (across July to September) since the 1990s (Table 26). The months of July and August have shown the most significant increases (Figure 63). While the average length of $POT_{>20°C}$ events has hovered around an average of 3 days per event since the 1960s, there has been an increase in the decadal total frequency of $POT_{>20°C}$ periods of that length from less than 60 days to 72-89 days in recent decades (Figure 64).

Water Temperature Exceedance Analyses

STAMP RIVER

A similar frequency analysis based on estimated daily mean water temperature indicates that the cumulative total number of $POT_{>19°C}$ dates per year has risen in the Stamp River over the past five decades; mostly in August, but with some spread to neighbouring months (Figure 65, Table 27). The average length of $POT_{>19°C}$ events has risen only slightly from an average of 8 days in the 1960s-1980s to 9.4 days since the 1990s, concurrent with an increase in the decadal total frequency of $POT_{>19°C}$ periods from ~27 to 47 per decade in the 2000s (Figure 66).

SPROAT RIVER

In the Sproat system the cumulative number of $POT_{>20°C}$ events in July and September have increased over the decades, which must be added to the $POT_{>20°C}$ events that characterize 75% of the days of August (Figure 67, Table 28). Thus, water temperatures in the Sproat River were estimated to be inhospitable to salmon for, on average, approximately 60 days of the July-September migration period in years since the 1990s. The annual frequency of continuous $POT_{>20°C}$ periods has remained constant (3-4 per year), but the average period length has steadily increased to almost 20 days in recent decades (Figure 68, Table 29).

Discharge Exceedance Analyses

STAMP RIVER

Low flows (< 25th percentile of ~24 cms[40]) were a rare event in the Stamp system in the 1960s and 1970s (Figure 69, Table 29), indicative perhaps of the cooler climatology during that period, plus the moderating effect of GCL dam operations on flow levels. Prior to dam construction in 1957, Stamp discharge levels were more variable, with observed flows less than the lower 5th percentile (~10 cms) occurring occasionally, including a record minimum of 2.5 cms in 1941 (WSC). Maximum daily flows in the pre-dam years also ranged widely, from ~50 cms (e.g., 1915, 1924, 1926, 1941, 1944) to the historical record of 251 cms (1956).

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[40] Significant rates of daily migration in the Stamp are not evident below this discharge threshold (Figure 56).

Since 1957, Stamp flows have not fallen below ~15 cms, but the frequency of dates for which discharge fell below the 25th percentile (~24 cms) rose rapidly in the 1980s and 1990s before retreating during the cooler, wetter 2000s (Figure 69). While the frequency of low flow events in recent decades (especially the 1990s) began to resemble conditions prior to installation of the GCL dam, the mean duration of low flow periods since the 1980s has remained below about 20 days – approximately half the length of low flow periods before dam construction (Figure 70, Table 29).

The frequency of high Stamp flows (>90th percentile of summer flows, ~90 cms), above which significant migration rates are infrequent, has been variable over the decades (Figure 71, Table 30), though the trend in the frequency and mean duration of continuous high flow periods has been downward since the 1950s (Figure 72). High flows occur mainly in June and early July prior to peak sockeye migration.

SPROAT RIVER

The occurrence of low flow conditions in Sproat River (<10th percentile of summer flow levels, ~5 cms) increased significantly between the 1960s and the 1990s, especially for the month of September (Figure 73). During the 1980s and 1990s, low flow dates occurred on average ~50 times during the Sockeye migration period. The 1990s were characterized by 9 low flow events ranging from 10-103 days in length (average: 58.7 days) (Figure 74, Table 31). While the total frequency of low flows dropped to 36 days on average in the 2000s (Figure 73), the average duration of drought periods remained high (~40 days), with a maximum duration of about two months (Table 31).

DISCUSSION

Overview of Sockeye Migration

Results from earlier studies focused on Sockeye return timing to the fishery (Steer and Hyatt 1987) or single-year tag-and-recovery efforts of adult Sockeye (Manzer et al. 1985; Hatfield Consultants 2013; Pellett et al. 2015) are considered here along with results from the current multi-year analysis as a source of inferences about Sockeye salmon migration behaviour (e.g., return timing, migration rates, etc.) in relation to variations in annual to seasonal environmental conditions.

The principal migration interval for adult Sockeye returning to Alberni Inlet and the Somass River system begins in early June and ends by mid-September. The time to 50% return to Alberni Inlet is centered near the week of July 4th (Steer and Hyatt 1987) and the all-year average (1974-2012) time to 50% passage at Stamp Falls for Great Central and Sproat-bound Sockeye salmon is about a week later around July 14-19th (results from current study). Adult Sockeye generally approach the outer waters of Barkley Sound from the northwest passing through "outside" fisheries executed in the area of the Broken Islands group. Results from a major PIT-tagging study in the summer of 2010 indicated that adult Sockeye travel at average rates of between 4.0-4.6 $km.d^{-1}$ through Barkley Sound and Alberni Inlet on their approach and entry into the lower Somass River near Port Alberni (Pellett et al. 2015). By contrast, a smaller study of archival-temperature tagged Sockeye in 2012 (Hatfield Consultants 2013) indicated that adult Sockeye moved at much faster rates averaging 12-24 $km.d^{-1}$ during a year of unusual environmental conditions (described below), Adult Sockeye are surface oriented (5-10 m depths) during their active migration stage through Barkley Sound and Alberni Inlet in early summer (Hatfield Consultants 2013). Consequently, they are generally exposed to mean temperatures of between 13.6 to 14.6°C and maximum temperatures no greater than 18.5°C. Later in the season when migration rates slow and adult Sockeye hold for extended periods in Alberni Inlet they occupy deeper depths (15-20m) where they are exposed to lower mean temperatures of between 9-12°C (Hatfield Consultants 2013 and Hyatt, unpublished data).

Migration Environment Challenges Revealed by Individual-year Studies and Analysis

Alberni Inlet and the Somass River system offer a variety of challenges to adult Sockeye returning to either Sproat or Great Central lakes. Relatively static features such as Sproat Falls and Stamp Falls have been historically challenging locations for passage for Sockeye salmon adults that several rounds of fish-way construction, maintenance and modification have been completed at both sites between 1927 and present to facilitate salmon passage (see Hyatt and Steer 1987 for review). PIT-tag study results (Pellett et al. 2015) indicate that although these locations are routinely passable now, short-term (i.e., daily) transit rates through the Sproat Falls fish-way increased in association with increasing temperature while transit rates through the Stamp Falls fish-way decreased at higher water levels during the summer (i.e., transit of fish-ways at Sproat and Stamp Fall are both influenced by seasonal variations in environmental conditions). In addition, dynamic water quantity and quality attributes (discharge, velocity fields, temperature and oxygen conditions) of Alberni Inlet and the Somass River system exhibit sufficient contrast to dramatically influence both Sockeye migration rates and success over greater distances (e.g., from the outside waters of Alberni Inlet to either Sproat or Stamp Falls locations) and over longer-term seasonal to annual temporal scales. For example, in the summer of 1990, adult Sockeye entry into the Somass River appeared to be impeded in association with onset of low flows (<40 cms) and especially high temperatures (>20°C) in the lower Somass River beginning in early July and persisting through late August (Appendix A).

An extended period of holding by the majority of the run in Alberni Inlet occurred in summer 1990 during which attempts at entry and migration through the lower Somass River by smaller groups of adult Sockeye were accompanied by mass mortality events – i.e., unprecedented numbers of dead and dying adult Sockeye (no less than 12,000) were recovered from river reaches below Stamp and Sproat Falls (Stucchi et al. 1990). Similar extreme environmental conditions emerged in 2004 and were again accompanied by evidence of high mortality rates (D. Dobson, DFO; pers. comm.) and extremely late entry (after Sept. 1st) by an anomalously high proportion of Sockeye migrants that year (>50% of all migrants to Sproat and Great Central, 2004 panel-plots in Appendix A). Thus, extreme migration delays, extended periods of holding in Alberni Inlet and mass mortality events for adult sockeye returning to Barkley Sound and the Somass River system have been clearly associated with seasonally anomalous environmental conditions (i.e., early onset of sub-average seasonal flows and water temperatures >20°C in the lower Somass River) in at least two years during the period of record.

Detailed results from the 2010 PIT-tagging study (Pellett et al. 2014) suggest that adult Sockeye migrations are likely influenced significantly by seasonal variations of environmental conditions in the lower Somass River in all years. During the 2010 study, Somass River discharge remained above the all-year seasonal average through the middle of August. In addition, Somass River temperatures were cool, failing to exceed 20°C for any interval lasting more than 2-3 days until late August. Consequently, 75% or more of all adult Sockeye had returned to Sproat and Great Central Lake by the end of the first week of August and there was little evidence of major migration delays or significant mortality events. In spite of this general outcome, simple correlational analysis of variations in migration rate of PIT-tagged adult Sockeye indicated high water temperatures, low precipitation and low flows throughout the Somass system were significantly ($p< 0.05$) associated with lower short-term (average daily) migration rates as the season progressed. However, the identity of the exact environmental driver of these results remained uncertain because all of the above environmental variables exhibited strong co-variance.

Further analysis was completed to identify the influence of environmental variables (temperature, discharge, precipitation and barometric pressure), summarized for possible influences on weekly mean migration rates. Application of multivariate least angular regression analysis (Pellett et al. 2015) to these data indicated that slower travel rates later in the season were associated with high temperature (Somass 7-day mean annual water temperature) and date. When date was removed from the model (i.e. because seasonal trends in water temperature co-vary with date), Somass water temperature alone accounted for up to 74% of the seasonal variation in Sockeye migration rates for fish travelling between ocean tagging locations at the outer end of Alberni Inlet and the lower Somass system. Weekly variations in Stamp River water levels (and/or discharge) accounted for a lesser amount of variation (17%). For Sproat-bound fish, average Somass water temperature (mean 3-day moving average) accounted for 96% of Sockeye travel rate variations (Table 16 of Pellett et al. 2015). Thus, even in the absence of major migration delays, Somass temperature variations appear to have been the principal environmental driver of Sockeye travel rates even in a relatively benign year like 2010.

As noted above, migration rates of adult Sockeye between ocean tagging locations at the outer end of Alberni Inlet and the lower Somass River were much faster for Sockeye fitted with archival temperature tags in summer 2012 (Hatfield Consultants 2013) than those implanted with PIT-tags in summer 2010 (Pellett et al. 2015). Extensive experience with use of PIT-tags and archival-temperature tags on salmon in previous studies (see refs in Pellett et al. 2015 and Hatfield Consultants 2013) make it extremely unlikely that the roughly 3-6 fold observed difference of average migration rates between years was attributable to the use of different tags. Consequently, the much faster migration rates observed in summer 2012 were more likely related to exceptionally favourable environmental conditions facilitating faster and earlier migration by Sockeye salmon. Although both 2010 and 2012 were years exhibiting generally favourable environmental conditions facilitating continuous migration by Sockeye adults, the exceptional conditions in 2012 included (1) anomalously high discharges (>100 cms relative to an all-year average closer to 50 cms) that persisted in the lower Somass system from May through late July and (2) Somass River temperatures that remained at or below 20°C for virtually the entire summer (see 2012 panel plots in Appendix A) relative to all-year averages that routinely exceeded 20°C for 2-3 weeks from mid-July to mid-August. One of the more interesting results from analysis of migration rates and environmental conditions for adult Sockeye fitted with PIT-tags in 2010 was that environmental conditions in the lower Somass river were more strongly related to subsequent migration rate variations exhibited by ocean-tagged fish than by fish tagged in-river at the Papermill Dam site. These results lend support to the view that adult sockeye "decisions" regarding commitment to active migration through Alberni Inlet (as opposed to holding there) and entry into the Somass River are made seaward of Papermill Dam.

Historic Migration Environment Challenges Revealed by All-year Analyses

The Somass watershed has, in the past, been home to a network of Environment Canada hydrological stations providing daily discharge and intermittent water temperature observations (Figure 2), but the density of stations has been significantly reduced in recent decades to the point where only one station, in the Sproat River, is currently active. Thus, in spite of the obvious impact of variable aquatic environmental conditions on Somass salmon populations, hourly to daily aquatic temperature and discharge observations were not generally available at various sites in the Somass system to match historical salmon migration observations from the past 38 years. Consequently, we developed statistical associations between continuous regional air temperature observations and intermittent water temperature observations to hind-cast daily water temperature trends at several sites (lower Somass River, Sproat Falls, Stamp River Falls) from 1918-2012. Use of calibration data sets yielded significant fits (simple Pearson and Spearman rank correlations ranging from 0.85 to 0.93, all $P < 0.0001$) for both logistic and linear regression models of centered multi-day mean air temperature versus daily mean water temperature at all sites (Tables 24-26). Further assessment of independent data sets for model validation also yielded generally strong associations between predicted and observed daily water temperatures at all sites (Tables 27-29, simple Pearson and Spearman rank correlations ranging from 0.69 to 0.94, all $P < 0.0001$).

Similarly, we used best-fit, statistical models for covariance of discharge observations at three sites (Sproat River, Somass River, Stamp Falls) to extend discontinued, discharge records for Somass and Stamp Falls sites based on a continuous data series (1913-2012) from a single Sproat River site. A parabolic, curvilinear relationship between Somass and Sproat daily flows provided reasonable estimates ($r=0.95$, $P<0.0001$) of observed Somass flows in the summer months of most years (Figures 12-13). A quadratic function describing the relationship between Stamp and Sproat River daily flows provided a reasonably strong basis for estimating missing Stamp River flows (correlation between observed and estimates Stamp flows = 0.96, $p<0.0001$, Figures 19-20). Success in identifying strong associations among these three Somass "system" sites with respect to daily water temperatures and flows was a pre-requisite for an all-year analysis to potentially identify additional relationships among these environmental variables and daily to seasonal migration variations exhibited by adult Sockeye returning to the Somass River, Sproat and Great Central lakes.

Results of our all-year (1974-2012) analyses indicated that time to 50% annual migration dates for adult Sockeye returning to Sproat and Great Central lakes occurred in mid-July when environmental conditions generally reach extreme enough river temperature and flow conditions (high and low respectively) to either impede or terminate fish entry from Alberni Inlet into the Somass River (e.g., as in the 1990 and 2004 examples discussed above). Temperatures encountered by adult Sockeye migrants vary among Somass tributaries dependent on specific migration routes. Thus, if Sproat and Great Central-bound fish experience temperatures of 18-20°C upon entry into the lower Somass River, then Great Central fish simultaneously entering the Stamp River will encounter temperatures between 17.5 to 19.5°C while fish simultaneously entering the relatively short (about 3 km) Sproat River will encounter temperatures between 21-23°C.

For Great Central-bound adult Sockeye, daily mean water temperatures of 18-19°C in the Stamp River (18.5-19.5°C in the lower Somass) appear to constitute a critical threshold for high versus low migration rates, especially during low flow periods. Evidence for a truly critical role of flow effects was somewhat equivocal in that high flows did not consistently reduce migration rates of Great Central-bound migrants although some evidence suggests flows greater than 80-90 cms at Stamp Falls may impede migration. The highest migration rates for Sproat-bound adult Sockeye occurred in association with temperatures of 17-21°C (i.e. 14-18°C in the lower Somass River) accompanied by discharges of 32-36 cms even though half of all available summer migration dates in the Sproat River are characterized by temperatures in excess of 20°C and flows of <10 cms. Further, there appears to be an interaction effect between temperature and flow on migration through Sproat River. Thus, although maximum daily migration rates through Sproat River occur at 18°C if flows are <10 cms, they occur at 19°C and continue through the short 3 km segment of the Sproat River even at temperatures between 21-23°C as long as discharge levels there are >24 cms. A somewhat more subjective assessment from consideration of annual anomaly plots of daily migration, water temperature and discharge (Appendix B) indicates that daily mean temperatures near 21°C constitute a critical threshold between high and low migration rates for Sproat-bound fish in most years, and especially during extended low-flow (<10-20 cms) periods.

Casual comparison of migratory behaviour of Sproat-bound and Great Central-bound adult Sockeye might suggest they exhibit different temperature thresholds with respect to their migratory behaviour. However, this inference depends critically on the spatial frame of reference under consideration. As noted above, results from a detailed PIT-tagging study (Pellett et al. 2015) indicate that the "decision" to maintain active migration from Alberni Inlet into the Somass River is made seaward of the Papermill Dam tagging site in the lower Somass River. By contrast, migration rates of adult Sockeye, following in-river tagging and subsequent migration, exhibited lower responsiveness to more immediate changes in environmental conditions in the Somass, Stamp, and Sproat rivers (Pellett et al. 2015). If properties of surface waters in the lower Somass and Alberni Inlet provide a set of common temperature and flow conditions used by both Sproat and Great Central Sockeye to trigger initiation of freshwater migration which fish then attempt to complete regardless of conditions encountered further upriver, then one might expect that temperature thresholds for continuous versus intermittent entry into the Somass River would be the same for both Great Central and Sproat fish. By contrast, if Sproat fish truly have an increased tolerance for higher temperatures than Great Central fish, one might expect that Sproat fish would exhibit a significantly higher threshold than Great Central Sockeye in the lower Somass River for the transition from continuous to intermittent and/or slowed seasonal entry. A crude test of these alternatives may be achieved by identifying the temperatures occurring in the lower Somass coincident with the temperature thresholds associated with transitions from high to lower migration rates in the Stamp and Sproat Rivers. As noted above, the temperature thresholds for these transitions at Sproat Falls and Stamp Falls are around 21-23°C and 18-19°C respectively which means that temperature thresholds for the transition from higher to lower migration rates in the lower Somass River at about the same times are 18-20°C and 17.5-18.5°C respectively for Sproat-bound versus Great central-bound fish. Although these results do not wholly rule out the possibility of a slightly higher tolerance for high temperatures by Sproat than Great Central fish, they do suggest the existence of very similar temperature thresholds for seasonal reductions in migration rates and the likelihood of entry from Alberni Inlet into the lower Somass River for both stocks of fish.

Future Migration Environment Challenges Revealed by All-year Analyses

Peak over threshold (POT) analyses were completed to review decadal scale trends in specific temperature and flow thresholds by site. The frequency and duration of "warm" weather episodes (daily mean temperature > 20°C) have steadily increased in the Somass region since the 1950's, with corresponding increases in the frequency and duration of equivalent "warm" water periods which may be stressful or lethal to salmon in both the Stamp and Sproat River systems. Further, adult Sockeye migration timing through the Somass system appears to have shifted to later dates in recent decades coincident with (1) increases in the frequency and duration of $\mathrm{POT}_{19^{\circ}\mathrm{C}}$ events in the Stamp (1990s and 2000s) and Sproat rivers (1980s through 2000s; Figures 65-68) and (2) increases in the frequency and duration of extremely low flows (<5 cms) in the Sproat River (1980s through 2000s; Figure 73-74). Sproat River minimum to median flows during the main Sockeye migration interval have decreased by 25-30% and mean flows have decreased from 12.9 to 9.8 cms over the past 50 years (trend of -0.5 cms per decade). Extreme low flows have also declined further from approximately 3 cms early in the series to only 1.3 cms in more recent decades suggesting that Sproat-bound Sockeye are now facing not only higher temperatures in the Sproat River relative to Great Central-bound fish in the Stamp River but also a higher proportion of dates during their main migration interval characterized by extremely low water levels (and implicitly discharge). Significantly, these low flow trends were not apparent in the Stamp River given stored water behind the Great Central Dam used to mitigate low summer flows especially after 1957. If above-average flows are key to migration success given almost certain exposure to stress inducing temperatures in excess of 18-19°C for Sproat fish in particular, then a long-term declining trend in summer water levels in the unregulated Sproat system, corresponding to an increase in the frequency and duration of "low flow" events (<5-10 cms), may present challenges to the sustainability of this stock as Sproat water temperatures continue to rise.

Finally, projections from global climate models suggesting continued increases of summer temperatures (1.5 to 4°C by 2100) and reductions to both winter snowpack and late summer flows in the Pacific Northwest and southern British Columbia due to climate change in the coming decades (Mote and Salathé 2009) are expected to stress wild salmon populations to their physical and physiological limits, potentially leading to general abundance declines and, in severe cases, extinctions. These projections do not auger well for sustainable production of Barkley Sound and Somass system Sockeye salmon. Given such a future, further human interventions (e.g., additional water storage, engineering of "cold-water" release structures for the Somass, Stamp and Sproat rivers) may be increasingly necessary to mitigate for trends in environmental conditions that, left unaddressed, will most certainly decrease future migration success of adult Sockeye salmon on their returns through Alberni Inlet and the Somass River system.

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	Date			Sockeye Migrants (3-d Avg)				Migration Rate (%)				
	Date Count	Min Date	Max Date	Min	Mean Daily	Max Daily	Annual Total	Mean Daily	P50	P75	P95	Max Daily
Year												
1976	98	18JUN	23SEP	51	2,673	15,991	261,966	1.02	0.36	1.69	3.73	6.10
1977	77	21JUN	23SEP	8	1,116	6,828	85,933	1.30	0.62	1.49	4.66	7.95
1978	102	14JUN	23SEP	5	1,181	8,799	120,442	0.98	0.52	1.16	3.77	7.31
1979	83	21JUN	23SEP	1	2,690	38,170	223,264	1.20	0.34	0.89	4.85	17.10
1980	112	13JUN	02OCT	57	1,475	11,575	165,168	0.89	0.60	1.00	2.56	7.01
1981	110	14JUN	01OCT	29	2,389	15,402	262,791	0.91	0.56	1.15	3.42	5.86
1982	109	14JUN	01OCT	5	1,413	15,069	154,058	0.92	0.22	1.23	3.38	9.78
1983	106	13JUN	26SEP	25	3,562	24,862	377,612	0.94	0.34	1.13	4.12	6.58
1984	127	29MAY	02OCT	2	1,050	6,207	133,310	0.79	0.44	0.88	2.95	4.66
1985	132	30MAY	08OCT	4	911	7,043	120,274	0.76	0.43	0.88	2.88	5.86
1986	161	01JUN	10NOV	6	856	15,075	137,807	0.62	0.27	0.65	2.15	10.94
1987	169	04JUN	20NOV	2	1,720	13,657	290,715	0.59	0.31	0.71	2.86	4.70
1988	160	10JUN	21NOV	1	1,292	8,639	206,676	0.63	0.37	0.87	2.62	4.18
1989	167	03JUN	20NOV	8	1,445	11,938	241,263	0.60	0.34	0.76	2.09	4.95
1990	155	08JUN	09NOV	13	1,159	6,633	179,604	0.65	0.33	0.89	2.46	3.69
1991	153	07JUN	11NOV	2	2,833	39,118	433,390	0.65	0.13	0.53	3.80	9.03
1992	163	01JUN	10NOV	4	1,197	8,345	195,118	0.61	0.32	0.77	1.86	4.28
1993	152	09JUN	07NOV	58	1,563	11,034	237,539	0.66	0.34	0.84	2.17	4.65
1994	161	02JUN	10NOV	1	705	6,715	113,493	0.62	0.21	0.67	2.87	5.92
1995	99	02JUN	19SEP	1	647	5,280	64,093	1.01	0.68	1.33	3.41	8.24
1996	150	06JUN	05NOV	1	1,100	13,088	165,025	0.67	0.36	0.68	2.68	7.93
1997	125	27MAY	29SEP	1	1,379	9,726	172,409	0.80	0.37	0.79	3.47	5.64
1998	173	22MAY	10NOV	1	1,585	18,612	274,279	0.58	0.44	0.81	1.49	6.79
1999	153	26MAY	06NOV	1	1,380	12,413	211,111	0.65	0.02	0.56	4.39	5.88
2000	131	31MAY	01NOV	1	548	3,271	71,730	0.76	0.47	0.91	2.64	4.56
2001	156	29MAY	31OCT	5	2,606	31,988	406,510	0.64	0.21	0.73	3.17	7.87
2002	185	07MAY	11NOV	1	1,521	22,046	281,336	0.54	0.21	0.46	2.24	7.84
2003	148	05JUN	06NOV	7	1,633	17,396	241,755	0.68	0.28	0.54	3.15	7.20
2004	174	22MAY	14NOV	1	1,182	20,000	205,618	0.57	0.15	0.60	2.60	9.73
2005	170	04MAY	01NOV	1	1,112	9,368	189,122	0.59	0.20	0.67	2.58	4.95
2006	154	16MAY	05NOV	1	854	8,829	131,568	0.65	0.21	0.70	3.53	6.71
2007	137	11MAY	10NOV	1	557	5,299	76,373	0.73	0.07	0.65	4.48	6.94
2008	136	14MAY	01NOV	0	544	4,179	74,024	0.74	0.14	1.02	3.58	5.65
2009	160	26MAY	08NOV	1	1,373	17,873	219,744	0.62	0.28	0.65	2.37	8.13
2010	144	29MAY	06NOV	1	2,328	18,151	335,204	0.69	0.22	1.06	3.46	5.41
2011	158	10MAY	03NOV	1	2,819	35,172	445,438	0.63	0.02	0.33	3.97	7.90
2012	102	24MAY	03SEP	2	1,463	13,081	149,202	0.98	0.18	0.76	4.85	8.77
1976-2012	5,152	18JUN	03SEP	0	1,486	39,118	7,654,964	0.72	0.29	0.79	3.10	17.10

Table 1. Annual migration statistics for Great Central Lake adult sockeye daily migrants, 1976-2012 (filtered for non-zero observations), documenting migration period, mean and maximum daily migrant and migration rate (%) estimates, and total escapement.

	Sproat Falls											
	Date			Sockeye Migrants (3-d Avg)				Migration Rate (%)				
	Date Count	Min Date	Max Date	Min	Mean Daily	Max Daily	Annual Total	Mean Daily	P50	P75	P95	Max Daily
Year												
1974	78	13JUN	03SEP	8	718	3,172	56,011	1.28	0.78	1.65	5.00	5.66
1975	88	14JUN	23SEP	12	626	2,370	55,069	1.14	0.84	1.68	2.79	4.30
1976	66	14JUN	21AUG	81	718	4,168	47,404	1.52	0.96	2.05	4.92	8.79
1977	78	14JUN	07SEP	12	823	3,069	64,219	1.28	1.11	2.12	3.45	4.78
1978	86	14JUN	15SEP	4	379	2,699	32,580	1.16	0.64	1.30	3.58	8.28
1979	94	14JUN	15SEP	21	782	9,397	73,473	1.06	0.57	1.20	3.36	12.79
1980	102	13JUN	22SEP	48	1,334	8,502	136,033	0.98	0.63	1.47	2.70	6.25
1981	102	14JUN	23SEP	2	1,282	7,541	130,812	0.98	0.45	1.16	4.02	5.76
1982	102	14JUN	23SEP	147	2,203	13,903	224,693	0.98	0.41	1.29	3.69	6.19
1983	124	24MAY	26SEP	17	2,079	13,153	257,793	0.81	0.31	0.83	3.42	5.10
1984	125	31MAY	02OCT	2	713	3,540	89,100	0.80	0.62	1.14	2.16	3.97
1985	133	29MAY	08OCT	1	1,105	9,602	146,951	0.75	0.37	0.88	2.96	6.53
1986	120	04JUN	02OCT	2	1,608	7,230	192,941	0.83	0.56	1.14	3.01	3.75
1987	109	22JUN	08OCT	13	1,393	10,380	151,835	0.92	0.29	1.05	3.48	6.84
1988	105	10JUN	22SEP	4	2,242	8,460	235,417	0.95	0.67	1.40	2.86	3.59
1989	119	02JUN	30SEP	30	1,412	7,719	167,987	0.84	0.49	1.17	2.77	4.59
1990	129	12JUN	19OCT	9	874	4,372	112,790	0.78	0.50	1.17	2.12	3.88
1991	113	10JUN	30SEP	19	1,854	18,736	209,475	0.88	0.32	0.78	4.61	8.94
1992	140	04JUN	21OCT	4	1,585	9,638	221,938	0.71	0.45	1.03	2.25	4.34
1993	132	04JUN	13OCT	42	1,555	11,138	205,289	0.76	0.40	0.81	3.27	5.43
1994	121	02JUN	30SEP	6	1,188	9,570	143,770	0.83	0.30	1.11	3.23	6.66
1995	92	05JUN	04SEP	4	1,113	4,405	102,400	1.09	0.78	1.59	3.22	4.30
1996	150	24MAY	21OCT	3	1,400	11,393	210,051	0.67	0.14	0.70	3.34	5.42
1997	124	27MAY	27SEP	2	1,156	5,576	143,403	0.81	0.47	1.27	2.59	3.89
1998	154	15MAY	15OCT	2	1,779	11,424	274,014	0.65	0.29	0.86	2.75	4.17
1999	130	24MAY	30SEP	21	1,305	7,235	169,636	0.77	0.29	1.43	2.70	4.27
2000	129	26MAY	18OCT	1	979	5,528	126,339	0.78	0.40	0.99	3.45	4.38
2001	184	14MAY	13NOV	4	2,019	19,322	371,518	0.54	0.19	0.47	2.53	5.20
2002	202	22APR	09NOV	2	1,090	15,375	220,189	0.50	0.09	0.33	2.99	6.98
2003	155	15MAY	16OCT	2	1,219	8,232	189,001	0.65	0.29	0.74	3.14	4.36
2004	170	18MAY	03NOV	2	882	6,207	149,947	0.59	0.25	0.75	2.15	4.14
2005	163	06MAY	20OCT	1	924	8,438	150,568	0.61	0.28	0.74	2.59	5.60
2006	136	12MAY	29SEP	1	466	4,005	63,357	0.74	0.26	1.01	3.16	6.32
2007	119	08MAY	03SEP	1	605	4,056	71,975	0.84	0.46	1.14	3.35	5.64
2008	108	20MAY	04SEP	2	1,082	5,393	116,844	0.93	0.45	1.53	3.17	4.62
2009	137	26MAY	11OCT	2	1,298	22,047	177,831	0.73	0.27	0.75	3.75	12.40
2010	116	20MAY	14OCT	3	2,375	11,950	275,468	0.86	0.35	1.28	3.61	4.34
2011	149	11MAY	06OCT	3	2,948	26,026	439,214	0.67	0.11	0.73	3.36	5.93
2012	117	10MAY	03SEP	7	1,964	13,329	229,755	0.85	0.31	1.20	3.51	5.80
1974-2014	4,801	13JUN	03SEP	1	1,341	26,026	6,437,090	0.81	0.38	1.06	3.15	12.79

Table 2. Annual migration statistics for Sproat Lake adult sockeye daily migrants, 1974-2012 (filtered for non-zero observations), documenting migration

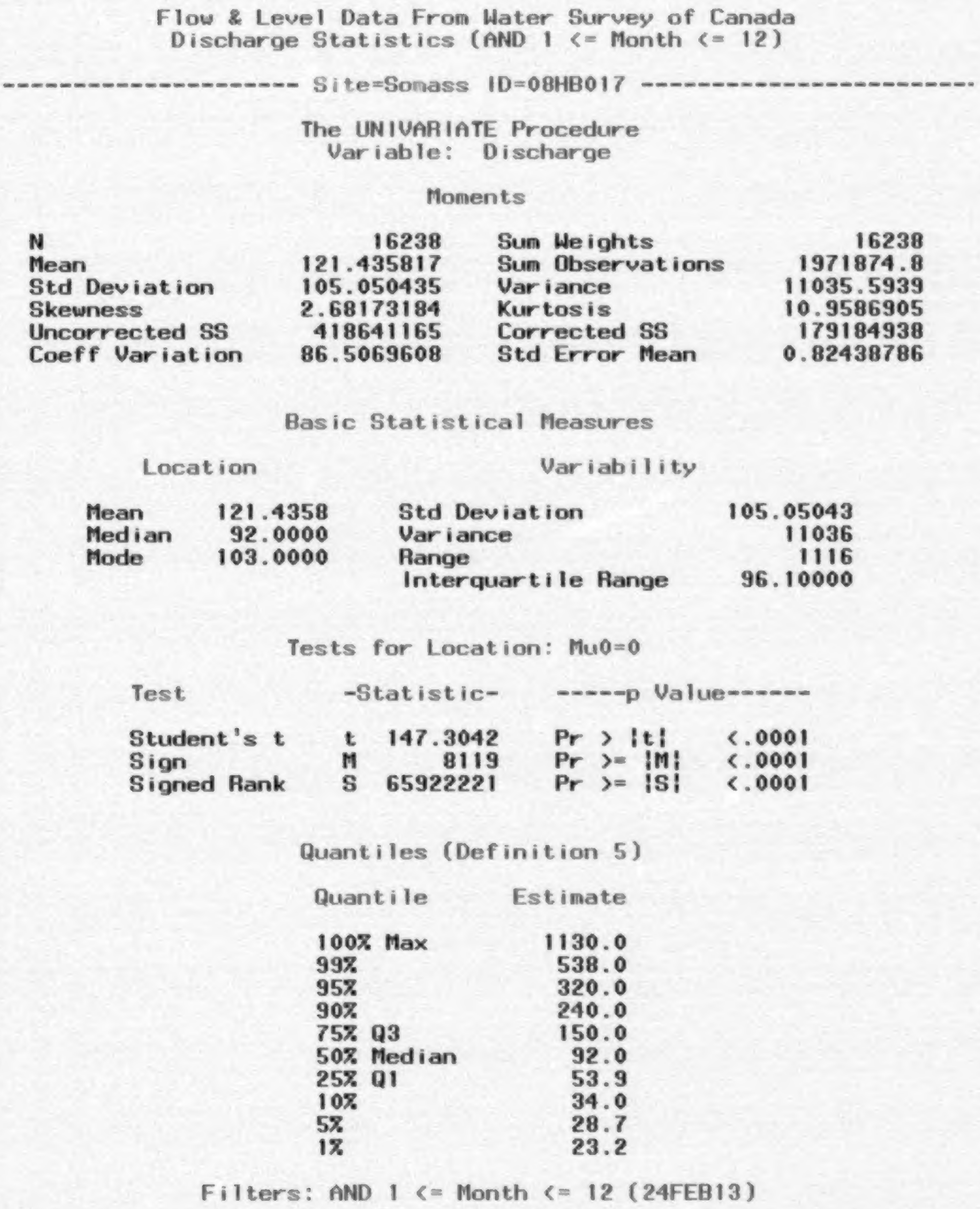
period, mean and maximum daily migrant and migration rate (%) estimates, and total escapement.

```
                 Flow & Level Data From Water Survey of Canada
                  Discharge Statistics (AND 1 <= Month <= 12)

---------------------- Site=Stamp ID=08HB010 ----------------------

                         The UNIVARIATE Procedure
                           Variable:  Discharge

                                 Moments

N                         19887    Sum Weights                 19887
Mean                 75.8846372    Sum Observations       1509117.78
Std Deviation        65.2940733    Variance               4263.31601
Skewness             2.75222853    Kurtosis               13.3645354
Uncorrected SS        199299157    Corrected SS           84780302.2
Coeff Variation      86.0438631    Std Error Mean         0.46300867


                        Basic Statistical Measures

            Location                    Variability

        Mean     75.88464     Std Deviation            65.29407
        Median   56.60000     Variance                     4263
        Mode     51.00000     Range                   776.51000
                              Interquartile Range      63.70000


                        Tests for Location: Mu0=0

          Test           -Statistic-    -----p Value------

          Student's t    t  163.8946    Pr > |t|    <.0001
          Sign           M    9943.5    Pr >= |M|   <.0001
          Signed Rank    S  98878164    Pr >= |S|   <.0001


                         Quantiles (Definition 5)

                          Quantile      Estimate

                          100% Max        779.00
                          99%             323.00
                          95%             197.00
                          90%             150.00
                          75% Q3           97.70
                          50% Median       56.60
                          25% Q1           34.00
                          10%              20.80
                          5%               13.70
                          1%                7.93

               Filters: AND 1 <= Month <= 12 (24FEB13)
```

Table 3. All-year and all-season discharge statistics for observed data from the Stamp River WSC Station 08HB010, 1914-1978.

```
---------------------- Site=Stamp ID=08HB010 ---------------------

                    The UNIVARIATE Procedure
             Variable:  Discharge  (Discharge (cms))

                              Moments

N                           1748    Sum Weights               1748
Mean                  44.9470252    Sum Observations       78567.4
Std Deviation         21.8309994    Variance            476.592533
Skewness              2.62612688    Kurtosis            9.58111441
Uncorrected SS        4363978.06    Corrected SS        832607.155
Coeff Variation         48.57051    Std Error Mean      0.52215916

                    Basic Statistical Measures

          Location                    Variability

      Mean     44.94703     Std Deviation            21.83100
      Median   38.20000     Variance                476.59253
      Mode     36.80000     Range                   205.20000
                            Interquartile Range      16.10000

                    Tests for Location: Mu0=0

        Test           -Statistic-    -----p Value------

        Student's t    t  86.07917    Pr > |t|    <.0001
        Sign           M       874    Pr >= |M|   <.0001
        Signed Rank    S    764313    Pr >= |S|   <.0001

                    Quantiles (Definition 5)

                    Quantile        Estimate

                    100% Max           223.0
                    99%                135.0
                    95%                 88.3
                    90%                 75.0
                    75% Q3              48.1
                    50% Median          38.2
                    25% Q1              32.0
                    10%                 28.2
                    5%                  26.6
                    1%                  23.2
                    0% Min              17.8
```

Table 4. All-year summer month (July-September) discharge statistics for observed data from the Stamp River WSC Station 08HB010, 1960-1978.



```
                  Flow & Level Data From Water Survey of Canada
                   Discharge Statistics (AND 1 <= Month <= 12)

--------------------- Site=Somass ID=08HB017 -----------------------

                            The UNIVARIATE Procedure
                             Variable:  Discharge

                                    Moments

    N                           16238    Sum Weights                 16238
    Mean                   121.435817    Sum Observations        1971874.8
    Std Deviation          105.050435    Variance               11035.5939
    Skewness               2.68173184    Kurtosis               10.9586905
    Uncorrected SS          418641165    Corrected SS            179184938
    Coeff Variation        86.5069608    Std Error Mean         0.82438786

                          Basic Statistical Measures

            Location                        Variability

        Mean     121.4358      Std Deviation            105.05043
        Median    92.0000      Variance                     11036
        Mode     103.0000      Range                         1116
                               Interquartile Range       96.10000

                          Tests for Location: Mu0=0

            Test             -Statistic-    -----p Value------

            Student's t      t  147.3042    Pr > |t|     <.0001
            Sign             M      8119    Pr >= |M|    <.0001
            Signed Rank      S  65922221    Pr >= |S|    <.0001

                           Quantiles (Definition 5)

                           Quantile       Estimate

                           100% Max         1130.0
                           99%               538.0
                           95%               320.0
                           90%               240.0
                           75% Q3            150.0
                           50% Median         92.0
                           25% Q1             53.9
                           10%                34.0
                           5%                 28.7
                           1%                 23.2

                     Filters: AND 1 <= Month <= 12 (24FEB13)
```

Table 5. All-year and all-season discharge statistics for observed data from the Somass River WSC Station 08HB017, 1957-2002.

```
-------------------- Site=Somass ID=08HB017 ------------------------

                    The UNIVARIATE Procedure
             Variable:  Discharge  (Discharge (cms))

                             Moments

N                             3924    Sum Weights                3924
Mean                    51.9267839    Sum Observations       203760.7
Std Deviation           32.0729114    Variance             1028.67164
Skewness                2.92982223    Kurtosis             14.4943493
Uncorrected SS          14616116.7    Corrected SS         4035478.86
Coeff Variation         61.7656418    Std Error Mean       0.51200463


                   Basic Statistical Measures

        Location                    Variability

    Mean     51.92678     Std Deviation              32.07291
    Median   42.50000     Variance                       1029
    Mode     34.30000     Range                     399.50000
                          Interquartile Range        27.50000


                   Tests for Location: Mu0=0

       Test           -Statistic-    -----p Value------

       Student's t    t  101.4186    Pr > |t|    <.0001
       Sign           M      1962    Pr >= |M|   <.0001
       Signed Rank    S   3850425    Pr >= |S|   <.0001


                    Quantiles (Definition 5)

                     Quantile       Estimate

                     100% Max          417.0
                     99%               173.0
                     95%               117.0
                     90%                88.9
                     75% Q3             59.8
                     50% Median         42.5
                     25% Q1             32.3
                     10%                26.5
                     5%                 24.2
                     1%                 20.9
                     0% Min             17.5
```

Table 6. All-year summer month (July-September) discharge statistics for observed data from the Somass River WSC Station 08HB017, 1960-2002.

```
                    Flow & Level Data From Water Survey of Canada
                     Discharge Statistics (AND 1 <= Month <= 12)

------------------------- Site=Sproat ID=08HB008 -------------------------

                            The UNIVARIATE Procedure
                             Variable:  Discharge

                                    Moments

    N                           32551    Sum Weights              32551
    Mean                   37.8891902    Sum Observations    1233331.03
    Std Deviation          34.1212407    Variance            1164.25907
    Skewness               2.13654299    Kurtosis            7.44172768
    Uncorrected SS         84626546.6    Corrected SS        37896632.7
    Coeff Variation        90.0553445    Std Error Mean      0.18912226

                          Basic Statistical Measures

                Location                    Variability

            Mean     37.88919     Std Deviation            34.12124
            Median   30.00000     Variance                     1164
            Mode     28.60000     Range                   366.62300
                                  Interquartile Range      35.60000

  Note: The mode displayed is the smallest of 2 modes with a count of 157.

                          Tests for Location: Mu0=0

              Test           -Statistic-    -----p Value------

              Student's t    t  200.3423    Pr > |t|    <.0001
              Sign           M   16275.5    Pr >= |M|   <.0001
              Signed Rank    S   2.649E8    Pr >= |S|   <.0001

                           Quantiles (Definition 5)

                           Quantile       Estimate

                           100% Max        367.000
                           99%             165.000
                           95%             104.000
                           90%              78.800
                           75% Q3           50.000
                           50% Median       30.000
                           25% Q1           14.400
                           10%               5.100

                    Filters: AND 1 <= Month <= 12 (24FEB13)
```

Table 7. All-year and all-season discharge statistics for observed data from the Sproat River WSC Station 08HB008, 1913-2012.

```
------------------- Site=Sproat ID=08HB008 -------------------

                    The UNIVARIATE Procedure
             Variable:  Discharge  (Discharge (cms))

                            Moments

N                          4876    Sum Weights                 4876
Mean                 9.82784001    Sum Observations      47920.5479
Std Deviation         9.7869002    Variance              95.7834155
Skewness             1.95541005    Kurtosis              4.87567297
Uncorrected SS       937899.628    Corrected SS           466944.15
Coeff Variation      99.5834302    Std Error Mean        0.14015652

                  Basic Statistical Measures

        Location                    Variability

    Mean     9.82784     Std Deviation             9.78690
    Median   6.26500     Variance                 95.78342
    Mode    11.40000     Range                    84.62300
                         Interquartile Range      10.19000

                  Tests for Location: Mu0=0

        Test           -Statistic-    -----p Value------

        Student's t    t  70.12046    Pr > |t|    <.0001
        Sign           M      2438    Pr >= |M|   <.0001
        Signed Rank    S   5945063    Pr >= |S|   <.0001

                  Quantiles (Definition 5)

                   Quantile      Estimate

                   100% Max        85.000
                   99%             42.800
                   95%             30.900
                   90%             23.200
                   75% Q3          13.200
                   50% Median       6.265
                   25% Q1           3.010
                   10%              1.680
                   5%               1.320
                   1%               0.597
                   0% Min           0.377
```

Table 8. All-year summer month (July-September) discharge statistics for observed data from the Sproat River WSC Station 08HB008, 1960-2012.

```
                                   Simple Statistics

Variable           N          Mean       Std Dev        Median       Minimum       Maximum

Somass          1477     119.55917     101.88619      89.80000      17.80000          1020
Stamp            662      80.42447      61.32117      61.20000      19.00000     634.00000
Sproat          1839      37.79956      34.86535      30.20000       0.41600     365.00000

                          Spearman Correlation Coefficients
                             Prob > |r| under H0: Rho=0
                               Number of Observations

                                 Somass         Stamp        Sproat

                   Somass       1.00000       0.96274       0.96000
                                               <.0001        <.0001
                                   1477           634          1477

                   Stamp        0.96274       1.00000       0.86497
                                 <.0001                      <.0001
                                    634           662           662

                   Sproat       0.96000       0.86497       1.00000
                                 <.0001        <.0001
                                   1477           662          1839
```

Table 9. Cross-correlation of calibration data from Somass, Stamp, and Sproat River daily mean discharge data (observed). Calibration data were sub-sampled from available discharge data by selecting the 10th, 20th, and 30th observations of each month (Jan-Dec) of the year for 1960-2012.

```
                                   Simple Statistics

Variable           N          Mean       Std Dev        Median       Minimum       Maximum

Somass           384      52.75964      40.24897      41.30000      17.80000     417.00000
Stamp            171      44.76433      22.91164      38.20000      19.00000     171.00000
Sproat           477       9.60607      10.27106       5.89000       0.41600      71.70000

                          Spearman Correlation Coefficients
                             Prob > |r| under H0: Rho=0
                               Number of Observations

                                 Somass         Stamp        Sproat

                   Somass       1.00000       0.94825       0.87551
                                               <.0001        <.0001
                                    384           168           384

                   Stamp        0.94825       1.00000       0.80304
                                 <.0001                      <.0001
                                    168           171           171

                   Sproat       0.87551       0.80304       1.00000
                                 <.0001        <.0001
                                    384           171           477
```

Table 10. Cross-correlation of calibration data from Somass, Stamp, and Sproat River daily mean discharge data (observed). Calibration data were sub-sampled from available discharge data by selecting the 10th, 20th, and 30th observations of each summer month (Jul-Sep) for the years 1960-2012.

	Water Temperature						Percentiles			
	Dates	Min	Mean	Max	Std	Skew	P25	P50	P75	P95
Year										
1991	37	16.72	18.91	21.48	1.35	0.25	17.8	18.8	19.7	21.3
1992	35	15.12	18.78	21.79	2.00	-0.41	17.1	19.3	20.1	21.6
1993	35	15.20	18.16	20.90	1.27	0.02	17.3	18.1	19.1	20.4
1994	38	16.81	19.66	23.02	1.42	0.32	18.5	19.5	20.6	22.1
1995	33	16.07	18.71	21.78	1.25	0.44	18.0	18.5	19.5	21.0
1996	35	15.54	18.69	21.83	1.83	0.15	17.1	18.8	20.3	21.7
1997	32	16.14	18.91	21.65	1.62	0.09	17.4	18.9	20.3	21.6
1998	28	16.31	19.89	22.32	1.65	-0.20	18.4	20.0	21.3	22.2
1999	10	13.66	17.84	19.63	1.91	-1.34	17.4	18.1	19.5	19.6
2000	12	16.27	18.68	20.92	1.40	-0.09	17.6	18.8	19.7	20.9
2001	7	17.05	18.62	19.51	0.84	-1.14	18.2	18.9	19.3	19.5
2002	10	17.58	19.60	21.50	1.55	-0.12	18.0	19.7	20.9	21.5
2003	7	16.59	19.76	21.24	1.56	-1.69	19.1	20.3	20.8	21.2
2004	8	16.55	19.50	22.15	2.00	-0.15	17.9	19.6	21.1	22.1
2005	9	15.64	19.00	21.32	2.22	-0.34	17.0	20.0	21.1	21.3
2006	12	16.00	18.81	20.89	1.43	-0.59	17.8	19.1	19.8	20.9
2008	13	15.86	18.55	20.46	1.24	-0.75	18.1	18.6	19.4	20.5
2009	14	15.81	19.68	25.01	2.28	0.76	18.6	19.3	21.4	25.0
2010	13	16.98	19.02	20.72	1.14	-0.51	18.0	19.3	19.9	20.7
2012	13	14.20	18.07	21.10	1.77	-0.78	17.3	18.8	19.0	21.1
All	401	13.66	18.93	25.01	1.65	-0.01	17.8	18.9	20.1	21.6

Table 11. Annual summary of daily summer month (Jul-Sep) water temperature data from Somass River at the Papermill Dam, 1991-2012 (Source: CATALYST PAPER ENVIRONMENTAL EFFLUENT MONITORING PROGRAM).

	Water Temperature						Percentiles			
	Dates	Min	Mean	Max	Std	Skew	P25	P50	P75	P95
Year										
2000	92	15.20	18.16	20.49	1.14	0.07	17.2	18.2	18.9	20.1
2001	87	16.15	18.08	20.57	0.93	0.47	17.5	18.0	18.6	20.0
2002	92	16.43	18.92	21.52	1.23	0.36	17.9	18.6	19.9	21.2
2003	92	16.70	19.35	22.26	1.29	-0.20	18.5	19.5	20.4	21.1
2004	22	18.66	20.12	21.85	0.84	-0.05	19.7	20.2	20.7	21.2
All	385	15.20	18.72	22.26	1.30	0.24	17.7	18.6	19.8	20.9

Table 12. Annual summary of Class 1 daily mean water temperature data for July-September from Stamp River data loggers installed at the Stamp Falls Fishway, 2000-2004 (Source: DFO SOUTH COAST). MEAN is average of daily mean temperatures from data logger readings for #DATES times per year. MIN and MAX are minimum and maximum of the daily mean temperatures (i.e., not observed extrema).

	Water Temperature						Percentiles			
	Dates	Min	Mean	Max	Std	Skew	P25	P50	P75	P95
Year										
1996	84	17.24	20.89	24.71	1.69	-0.26	19.8	21.0	22.1	23.3
2000	83	17.98	20.51	22.77	1.35	0.15	19.4	20.4	21.6	22.6
2002	91	18.36	21.10	23.38	1.30	-0.22	20.0	21.3	22.1	23.0
2003	43	20.48	22.54	25.13	1.17	0.20	21.5	22.5	23.3	24.5
2009	76	19.27	22.66	26.17	1.98	0.22	21.1	22.6	24.3	26.0
2010	90	17.99	20.80	23.88	1.72	-0.13	19.2	20.9	22.4	23.2
All	467	17.24	21.28	26.17	1.77	0.20	19.9	21.4	22.6	24.3

Table 13. Annual summary of Class 1 daily mean water temperature data for July-September from Sproat River data loggers installed at the Sproat Falls Fishway, 1996, 2000-2003 (Source: DFO SALMON IN REGIONAL ECOSYSTEMS and DFO SOUTH COAST), 2009-2010 (Source: BC CONSERVATION FOUNDATION). MEAN is average of daily mean temperatures from data logger readings for #DATES times per year. MIN and MAX are minimum and maximum of the daily mean temperatures (i.e., not observed extrema).

	Calibration		Validation	
	Warming	Cooling	Warming	Cooling
	Observations	Observations	Observations	Observations
Year				
1991	20	40		
1992			23	42
1993			34	40
1994			33	38
1995			27	35
1996			26	40
1997			29	30
1998			26	28
1999			16	15
2000	10	11		
2001	16	9		
2002			11	11
2003	13	12		
2004	15	9		
2005			10	11
2006			15	15
2007			0	0
2008			14	15
2009	15	16		
2010	15	16		
2011			0	0
2012			13	10

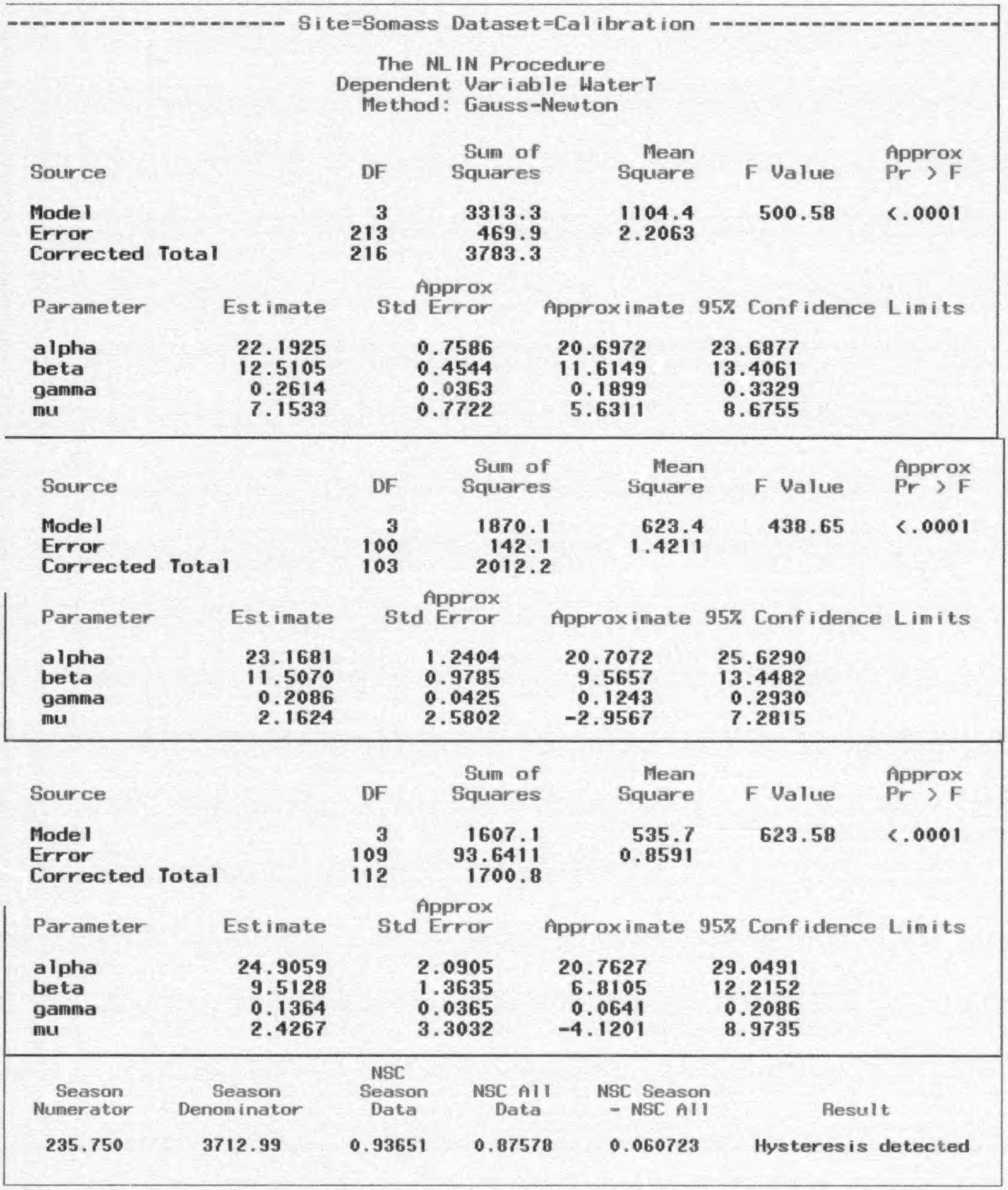
Table 14. Number of annual water temperature observations available for Somass River air/water temperature analyses, partitioned into warming and cooling seasons for seasonal relationships. Air/water temperature model calibration data years were selected based on strength of association between air and water time-series and range of temperature observations.

	Calibration		Validation	
	Warming	Cooling	Warming	Cooling
	Observations	Observations	Observations	Observations
Year				
1991			0	0
1992			0	0
1993			78	0
1994			0	0
1995			85	0
1996			79	0
1997			0	0
1998			0	0
1999			0	0
2000	49	145		
2001	205	154		
2002	210	154		
2003	210	154		
2004	204	0		
2005			0	0
2006			0	0
2007			0	0
2008			0	0
2009			142	40
2010			45	55
2011			0	0
2012			0	0

Table 15. Number of annual water temperature observations available for Stamp River air/water temperature analyses, partitioned into warming and cooling seasons for seasonal relationships. Air/water temperature model calibration data years were selected based on strength of association between air and water time-series and range of temperature observations.

	Calibration		Validation	
	Warming	Cooling	Warming	Cooling
	Observations	Observations	Observations	Observations
Year				
1996	20	84		
1997			0	0
1998			0	0
1999			0	0
2000	40	102		
2001			10	0
2002	69	80		
2003			39	16
2004			0	0
2005			0	0
2006			0	0
2007			0	0
2008			0	0
2009	242	18		
2010	45	61		
2011			0	0
2012			0	0

Table 16. Number of annual water temperature observations available for Sproat River air/water temperature analyses, partitioned into warming and cooling seasons for seasonal relationships. Air/water temperature model calibration data years were selected based on strength of association between air and water time-series and range of temperature observations.



```
---------------------- Site=Somass Dataset=Calibration ----------------------

                           The NLIN Procedure
                     Dependent Variable WaterT
                        Method: Gauss-Newton

                                   Sum of        Mean               Approx
Source                    DF      Squares      Square    F Value    Pr > F

Model                      3       3313.3      1104.4     500.58    <.0001
Error                    213        469.9      2.2063
Corrected Total          216       3783.3

                                  Approx
Parameter      Estimate      Std Error    Approximate 95% Confidence Limits

alpha           22.1925         0.7586     20.6972      23.6877
beta            12.5105         0.4544     11.6149      13.4061
gamma            0.2614         0.0363      0.1899       0.3329
mu               7.1533         0.7722      5.6311       8.6755

                                   Sum of        Mean               Approx
Source                    DF      Squares      Square    F Value    Pr > F

Model                      3       1870.1       623.4     438.65    <.0001
Error                    100        142.1      1.4211
Corrected Total          103       2012.2

                                  Approx
Parameter      Estimate      Std Error    Approximate 95% Confidence Limits

alpha           23.1681         1.2404     20.7072      25.6290
beta            11.5070         0.9785      9.5657      13.4482
gamma            0.2086         0.0425      0.1243       0.2930
mu               2.1624         2.5802     -2.9567       7.2815

                                   Sum of        Mean               Approx
Source                    DF      Squares      Square    F Value    Pr > F

Model                      3       1607.1       535.7     623.58    <.0001
Error                    109      93.6411      0.8591
Corrected Total          112       1700.8

                                  Approx
Parameter      Estimate      Std Error    Approximate 95% Confidence Limits

alpha           24.9059         2.0905     20.7627      29.0491
beta             9.5128         1.3635      6.8105      12.2152
gamma            0.1364         0.0365      0.0641       0.2086
mu               2.4267         3.3032     -4.1201       8.9735

                            NSC
  Season        Season     Season    NSC All    NSC Season
 Numerator   Denominator    Data      Data       - NSC All          Result

  235.750      3712.99     0.93651   0.87578     0.060723     Hysteresis detected
```

Table 17. Logistic regression output for air/water temperature relationship between the ROBERTSON CREEK STANDARD 7d-CMAT (air temperature index) and calibration data for Somass River daily spot water temperatures: seasons combined (top); warming season (middle); cooling season (bottom).

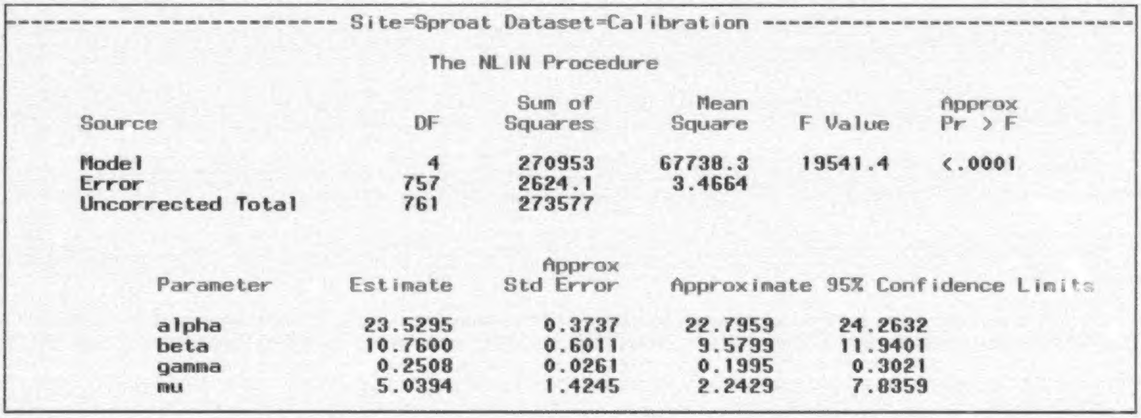
```
----------------------- Site=Stamp Dataset=Calibration -----------------------

                         The NLIN Procedure
                     Dependent Variable WaterT
                      Method: Gauss-Newton

                                      Sum of        Mean                  Approx
 Source                      DF      Squares      Square     F Value     Pr > F

 Model                        4       244156     61039.0     22498.2     <.0001
 Error                     1481       4018.0      2.7131
 Uncorrected Total         1485       248174

                                     Approx
 Parameter      Estimate          Std Error    Approximate 95% Confidence Limits

 alpha           20.2146            0.2296      19.7643      20.6649
 beta            10.5453            0.1318      10.2867      10.8039
 gamma            0.2971            0.0132       0.2711       0.3231
 mu               4.1219            0.2058       3.7182       4.5255
```

```
                                      Sum of        Mean                  Approx
 Source                      DF      Squares      Square     F Value     Pr > F

 Model                        3      24776.9      8259.0     5375.81     <.0001
 Error                      874       1342.7      1.5363
 Corrected Total            877      26119.6

                                     Approx
 Parameter      Estimate          Std Error    Approximate 95% Confidence Limits

 alpha           19.9413            0.2636      19.4240      20.4587
 beta            11.0074            0.1358      10.7409      11.2739
 gamma            0.2904            0.0131       0.2647       0.3162
 mu               3.2683            0.2092       2.8577       3.6789
```

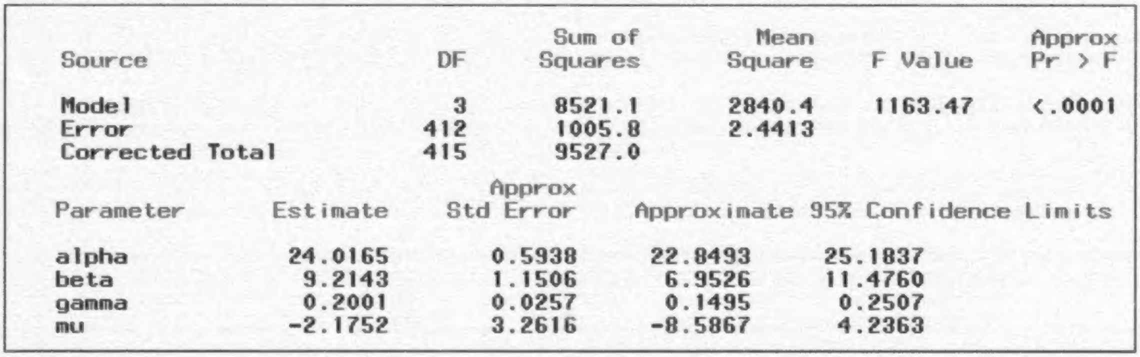
```
                                      Sum of        Mean                  Approx
 Source                      DF      Squares      Square     F Value     Pr > F

 Model                        3      15727.3      5242.4     4474.29     <.0001
 Error                      603        706.5      1.1717
 Corrected Total            606      16433.8

                                     Approx
 Parameter      Estimate          Std Error    Approximate 95% Confidence Limits

 alpha           21.7005            0.3482      21.0167      22.3843
 beta             9.1445            0.2222       8.7082       9.5808
 gamma            0.2148            0.0135       0.1883       0.2413
 mu               3.4651            0.4713       2.5395       4.3906
```

```
----------------------- Site=Stamp Dataset=Calibration ---------------------------

                              NSC
   Season        Season      Season     NSC All    NSC Season
 Numerator    Denominator     Data        Data      - NSC All          Result

  2049.26       42553.43     0.95184     0.91239     0.039452    Hysteresis detected
```

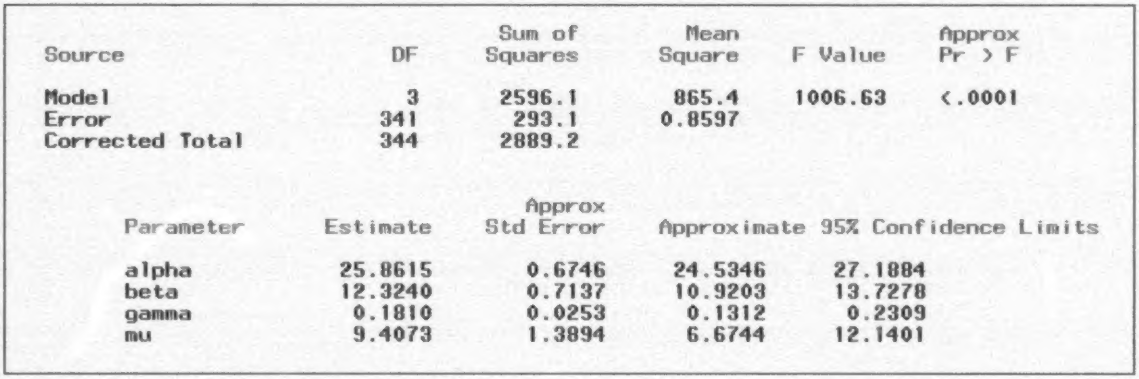
Table 18. Logistic regression output for air/water temperature relationship between the ROBERTSON CREEK STANDARD 7d-CMAT (air temperature index) and calibration data for Stamp River daily mean water temperatures: seasons combined (top); warming season (middle); cooling season (bottom).



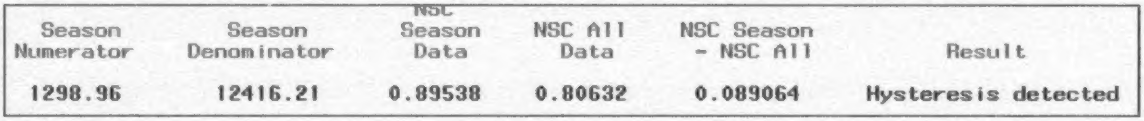
```
------------------------ Site=Sproat Dataset=Calibration ----------------------------

                              The NLIN Procedure

                                        Sum of        Mean                  Approx
   Source                     DF       Squares      Square    F Value     Pr > F

   Model                       4        270953     67738.3    19541.4     <.0001
   Error                     757        2624.1      3.4664
   Uncorrected Total         761        273577

                                          Approx
        Parameter      Estimate       Std Error     Approximate 95% Confidence Limits

        alpha           23.5295          0.3737       22.7959       24.2632
        beta            10.7600          0.6011        9.5799       11.9401
        gamma            0.2508          0.0261        0.1995        0.3021
        mu               5.0394          1.4245        2.2429        7.8359
```



```
                                        Sum of        Mean                  Approx
   Source                     DF       Squares      Square    F Value     Pr > F

   Model                       3        8521.1      2840.4    1163.47     <.0001
   Error                     412        1005.8      2.4413
   Corrected Total           415        9527.0

                                          Approx
   Parameter         Estimate         Std Error     Approximate 95% Confidence Limits

   alpha              24.0165            0.5938       22.8493       25.1837
   beta                9.2143            1.1506        6.9526       11.4760
   gamma               0.2001            0.0257        0.1495        0.2507
   mu                 -2.1752            3.2616       -8.5867        4.2363
```

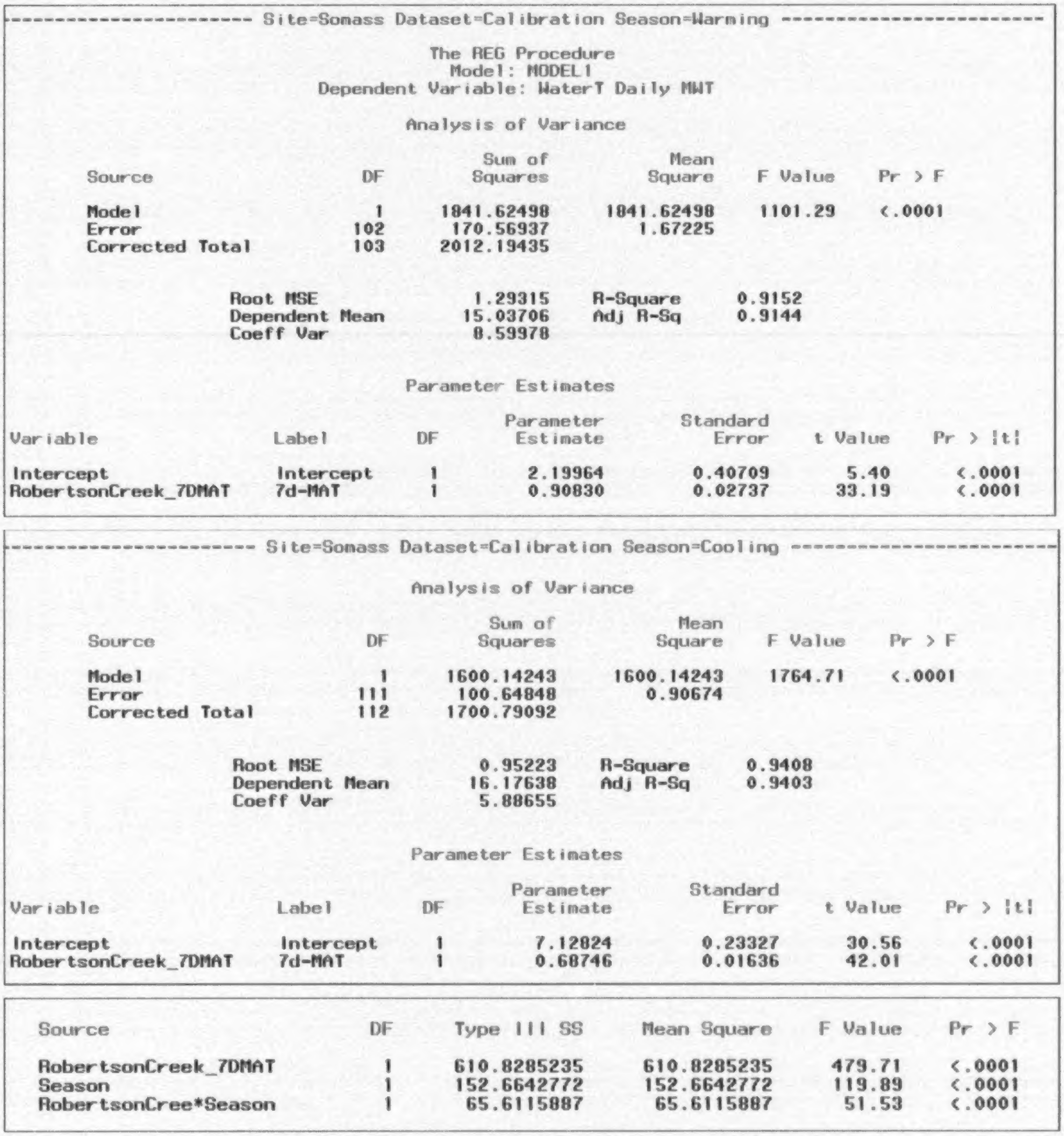


```
                                        Sum of        Mean                  Approx
   Source                     DF       Squares      Square    F Value     Pr > F

   Model                       3        2596.1       865.4    1006.63     <.0001
   Error                     341         293.1      0.8597
   Corrected Total           344        2889.2

                                          Approx
        Parameter      Estimate       Std Error     Approximate 95% Confidence Limits

        alpha           25.8615          0.6746       24.5346       27.1884
        beta            12.3240          0.7137       10.9203       13.7278
        gamma            0.1810          0.0253        0.1312        0.2309
        mu               9.4073          1.3894        6.6744       12.1401
```



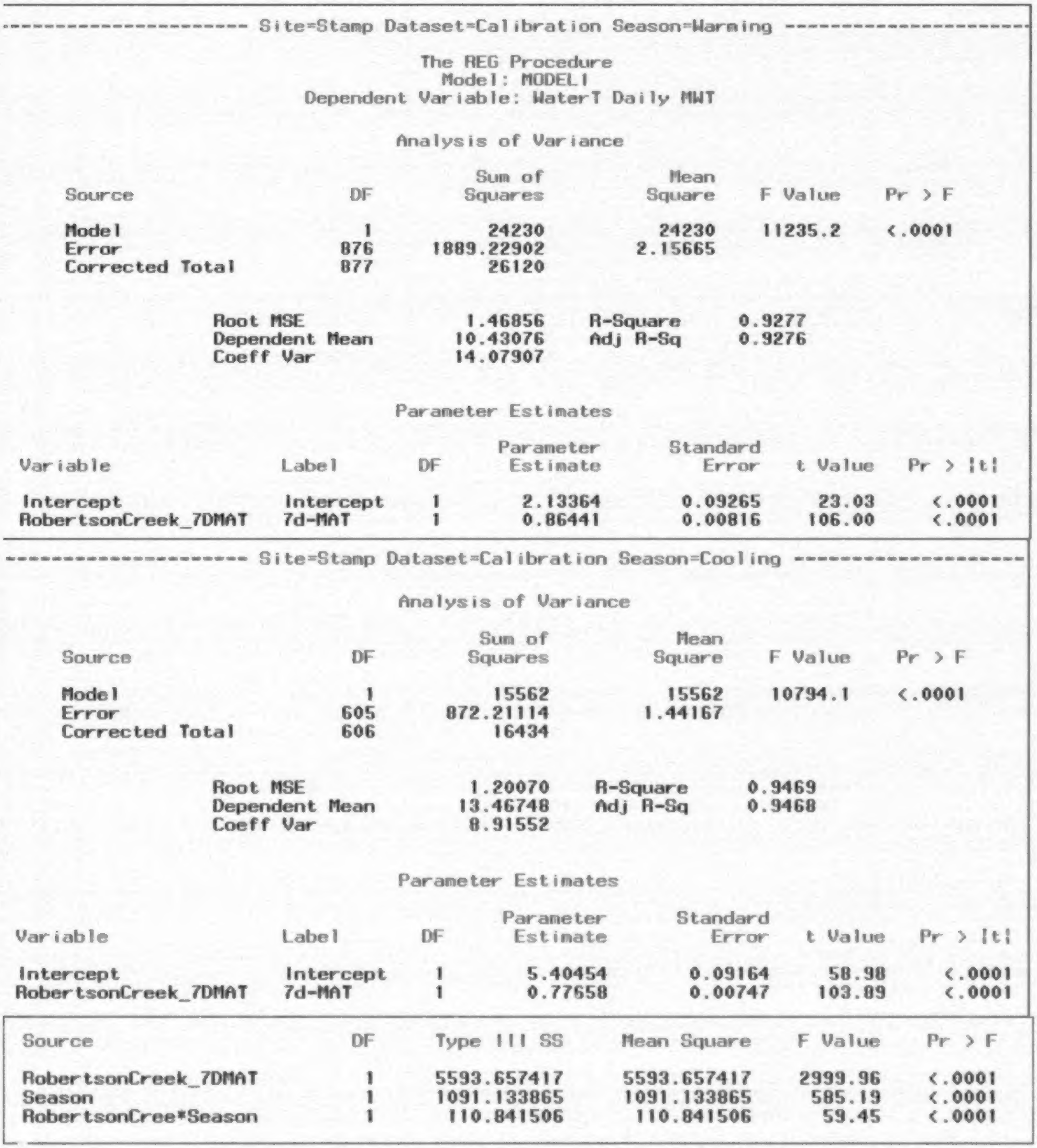
```
                                   NSC
   Season          Season        Season     NSC All    NSC Season
 Numerator      Denominator        Data        Data     - NSC All             Result

  1298.96          12416.21     0.89538     0.80632      0.089064    Hysteresis detected
```

Table 19. Logistic regression output for air/water temperature relationship between the ROBERTSON CREEK STANDARD 7d-CMAT (air temperature index) and calibration data for Sproat River daily mean water temperatures: seasons combined (top); warming season (middle); cooling season (bottom).



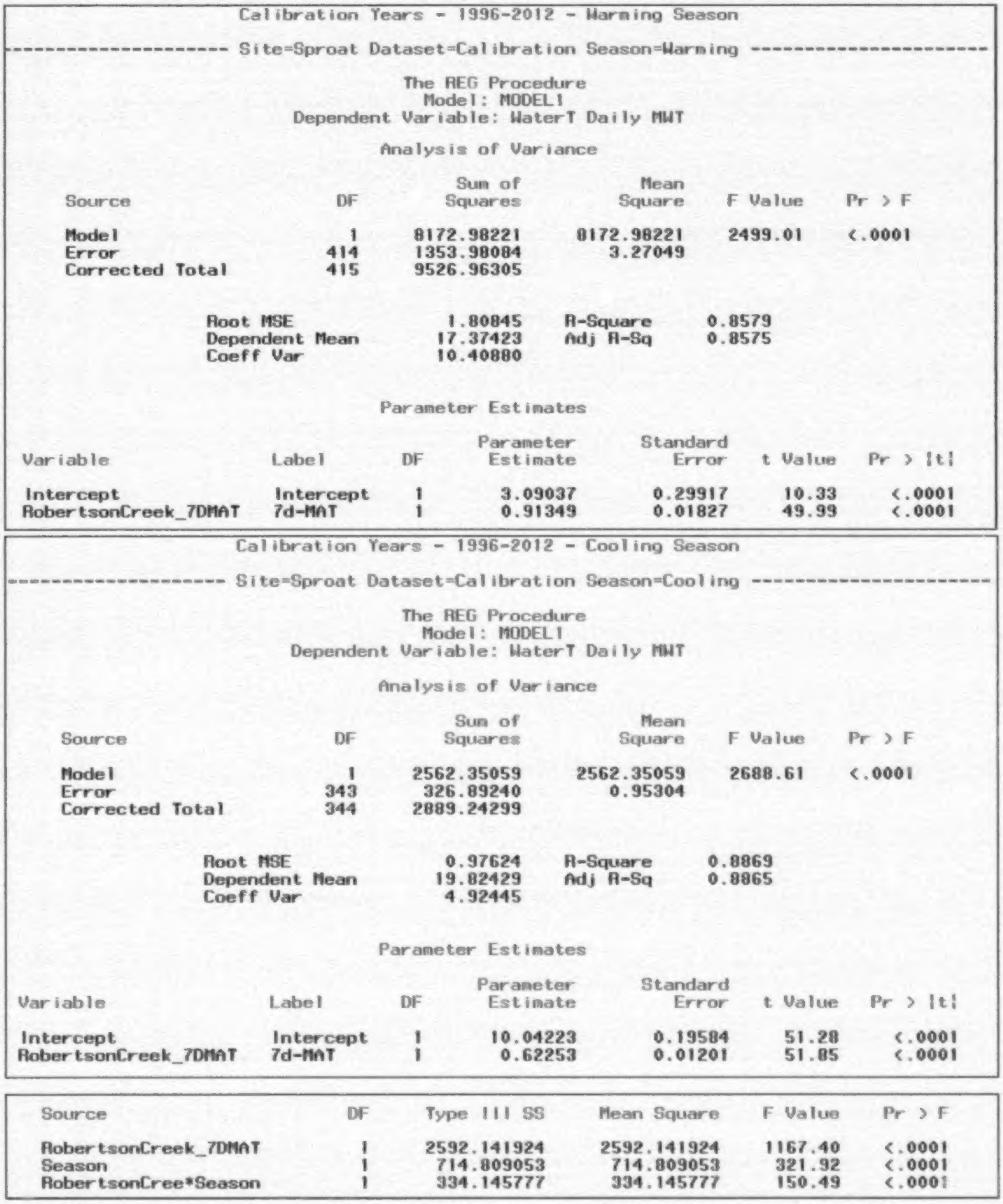
```
---------------------- Site=Somass Dataset=Calibration Season=Warming ----------------------

                                The REG Procedure
                                  Model: MODEL1
                       Dependent Variable: WaterT Daily MWT

                              Analysis of Variance

                                      Sum of           Mean
        Source                 DF      Squares         Square    F Value    Pr > F

        Model                   1   1841.62498     1841.62498    1101.29    <.0001
        Error                 102    170.56937        1.67225
        Corrected Total       103   2012.19435

                 Root MSE              1.29315    R-Square     0.9152
                 Dependent Mean       15.03706    Adj R-Sq     0.9144
                 Coeff Var             8.59978

                              Parameter Estimates

                                              Parameter       Standard
Variable              Label           DF       Estimate          Error    t Value    Pr > |t|

Intercept             Intercept        1        2.19964        0.40709       5.40      <.0001
RobertsonCreek_7DMAT  7d-MAT           1        0.90830        0.02737      33.19      <.0001

---------------------- Site=Somass Dataset=Calibration Season=Cooling ----------------------

                              Analysis of Variance

                                      Sum of           Mean
        Source                 DF      Squares         Square    F Value    Pr > F

        Model                   1   1600.14243     1600.14243    1764.71    <.0001
        Error                 111    100.64848        0.90674
        Corrected Total       112   1700.79092

                 Root MSE              0.95223    R-Square     0.9408
                 Dependent Mean       16.17638    Adj R-Sq     0.9403
                 Coeff Var             5.88655

                              Parameter Estimates

                                              Parameter       Standard
Variable              Label           DF       Estimate          Error    t Value    Pr > |t|

Intercept             Intercept        1        7.12824        0.23327      30.56      <.0001
RobertsonCreek_7DMAT  7d-MAT           1        0.68746        0.01636      42.01      <.0001

     Source                    DF     Type III SS     Mean Square    F Value    Pr > F

     RobertsonCreek_7DMAT       1     610.8285235     610.8285235     479.71    <.0001
     Season                     1     152.6642772     152.6642772     119.89    <.0001
     RobertsonCree*Season       1      65.6115887      65.6115887      51.53    <.0001
```

Table 20. Linear regression output for air/water temperature relationship between the ROBERTSON CREEK STANDARD 7d-CMAT (air temperature index) and calibration data for Somass River daily spot water temperatures: warming season (top); cooling season (middle). Type III sum of squares for season effect and season interaction effect are highly significant (bottom), indicating that hysteresis exists and that seasonal models provide the best fit to the data.



```
--------------------- Site=Stamp Dataset=Calibration Season=Warming ---------------------

                              The REG Procedure
                                Model: MODEL1
                      Dependent Variable: WaterT Daily MWT

                            Analysis of Variance

                                   Sum of          Mean
Source                   DF       Squares        Square    F Value    Pr > F

Model                     1         24230         24230    11235.2    <.0001
Error                   876    1889.22902       2.15665
Corrected Total         877         26120

          Root MSE              1.46856    R-Square     0.9277
          Dependent Mean       10.43076    Adj R-Sq     0.9276
          Coeff Var            14.07907

                            Parameter Estimates

                                         Parameter       Standard
Variable              Label        DF     Estimate          Error    t Value    Pr > |t|

Intercept             Intercept     1      2.13364        0.09265      23.03      <.0001
RobertsonCreek_7DMAT  7d-MAT        1      0.86441        0.00816     106.00      <.0001

--------------------- Site=Stamp Dataset=Calibration Season=Cooling ---------------------

                            Analysis of Variance

                                   Sum of          Mean
Source                   DF       Squares        Square    F Value    Pr > F

Model                     1         15562         15562    10794.1    <.0001
Error                   605     872.21114       1.44167
Corrected Total         606         16434

          Root MSE              1.20070    R-Square     0.9469
          Dependent Mean       13.46748    Adj R-Sq     0.9468
          Coeff Var             8.91552

                            Parameter Estimates

                                         Parameter       Standard
Variable              Label        DF     Estimate          Error    t Value    Pr > |t|

Intercept             Intercept     1      5.40454        0.09164      58.98      <.0001
RobertsonCreek_7DMAT  7d-MAT        1      0.77658        0.00747     103.89      <.0001

Source                   DF     Type III SS     Mean Square    F Value    Pr > F

RobertsonCreek_7DMAT      1     5593.657417     5593.657417    2999.96    <.0001
Season                    1     1091.133865     1091.133865     585.19    <.0001
RobertsonCree*Season      1      110.841506      110.841506      59.45    <.0001
```

Table 21. Linear regression output for air/water temperature relationship between the ROBERTSON CREEK STANDARD 7d-CMAT (air temperature index) and calibration data for Stamp River daily mean water temperatures: warming season (top); cooling season (middle). Type III sum of squares for season effect and season interaction effect are highly significant (bottom), indicating that hysteresis exists and that seasonal models provide the best fit to the data.



```
                     Calibration Years - 1996-2012 - Warming Season

-------------------- Site=Sproat Dataset=Calibration Season=Warming ---------------------

                               The REG Procedure
                                 Model: MODEL1
                     Dependent Variable: WaterT Daily MWT

                             Analysis of Variance

                                    Sum of           Mean
    Source                  DF     Squares         Square    F Value    Pr > F

    Model                    1   8172.98221     8172.98221   2499.01    <.0001
    Error                  414   1353.98084        3.27049
    Corrected Total        415   9526.96305


                 Root MSE              1.80845    R-Square     0.8579
                 Dependent Mean       17.37423    Adj R-Sq     0.8575
                 Coeff Var            10.40880


                             Parameter Estimates

                                          Parameter       Standard
Variable               Label       DF      Estimate          Error    t Value    Pr > |t|

Intercept              Intercept    1       3.09037        0.29917      10.33      <.0001
RobertsonCreek_7DMAT   7d-MAT       1       0.91349        0.01827      49.99      <.0001
```

```
                     Calibration Years - 1996-2012 - Cooling Season

-------------------- Site=Sproat Dataset=Calibration Season=Cooling ---------------------

                               The REG Procedure
                                 Model: MODEL1
                     Dependent Variable: WaterT Daily MWT

                             Analysis of Variance

                                    Sum of           Mean
    Source                  DF     Squares         Square    F Value    Pr > F

    Model                    1   2562.35059     2562.35059   2688.61    <.0001
    Error                  343    326.89240        0.95304
    Corrected Total        344   2889.24299


                 Root MSE              0.97624    R-Square     0.8869
                 Dependent Mean       19.82429    Adj R-Sq     0.8865
                 Coeff Var             4.92445


                             Parameter Estimates

                                          Parameter       Standard
Variable               Label       DF      Estimate          Error    t Value    Pr > |t|

Intercept              Intercept    1      10.04223        0.19584      51.28      <.0001
RobertsonCreek_7DMAT   7d-MAT       1       0.62253        0.01201      51.85      <.0001
```

```
  Source                    DF     Type III SS     Mean Square    F Value    Pr > F

  RobertsonCreek_7DMAT       1     2592.141924     2592.141924    1167.40    <.0001
  Season                     1      714.809053      714.809053     321.92    <.0001
  RobertsonCree*Season       1      334.145777      334.145777     150.49    <.0001
```

Table 22. Linear regression output for air/water temperature relationship between the ROBERTSON CREEK STANDARD 7d-CMAT (air temperature index) and calibration data for Sproat River daily mean water temperatures: warming season (top); cooling season (middle). Type III sum of squares for season effect and season interaction effect are highly significant (bottom), indicating that hysteresis exists and that seasonal models provide the best fit to the data.

```
------------- Site=Somass Dataset=Validation Season=Warming ------------

                 Pearson Correlation Coefficients, N = 277
                        Prob > |r| under H0: Rho=0

                                 Logistic          Linear
                                    Model           Model
                                    Water           Water
                                     Temp            Temp

                WaterT            0.90303         0.89935
                Daily MWT          <.0001          <.0001


                Spearman Correlation Coefficients, N = 277
                        Prob > |r| under H0: Rho=0

                                 Logistic          Linear
                                    Model           Model
                                    Water           Water
                                     Temp            Temp

                WaterT            0.87681         0.87681
                Daily MWT          <.0001          <.0001


--------- Site=Somass Dataset=Validation Season=Cooling -----------

                  Pearson Correlation Coefficients
                     Prob > |r| under H0: Rho=0
                       Number of Observations

                               Logistic          Linear
                                  Model           Model
                                  Water           Water
                                   Temp            Temp

             WaterT             0.95132         0.94925
             Daily MWT           <.0001          <.0001
                                    328             328


                 Spearman Correlation Coefficients
                     Prob > |r| under H0: Rho=0
                       Number of Observations

                               Logistic          Linear
                                  Model           Model
                                  Water           Water
                                   Temp            Temp

             WaterT             0.94950         0.94950
             Daily MWT           <.0001          <.0001
                                    328             328
```

Table 23. Comparison of Pearson (least squares) and Spearman (rank) correlation coefficients for observed versus estimated (from logistic and linear models) daily mean water temperature for air/water temperature relationships for validation data years in the Somass River: warming season (top); cooling season (bottom). Analysis indicates equal predictive power between the two model types.

```
----------- Site=Stamp Dataset=Validation Season=Warming -----------

              Pearson Correlation Coefficients, N = 429
                      Prob > |r| under H0: Rho=0

                              Logistic          Linear
                                 Model           Model
                                 Water           Water
                                  Temp            Temp

            WaterT             0.92874         0.94644
            Daily MWT           <.0001          <.0001


             Spearman Correlation Coefficients, N = 429
                     Prob > |r| under H0: Rho=0

                              Logistic          Linear
                                 Model           Model
                                 Water           Water
                                  Temp            Temp

            WaterT             0.94096         0.94096
            Daily MWT           <.0001          <.0001


----------- Site=Stamp Dataset=Validation Season=Cooling -----------

              Pearson Correlation Coefficients, N = 95
                      Prob > |r| under H0: Rho=0

                              Logistic          Linear
                                 Model           Model
                                 Water           Water
                                  Temp            Temp

            WaterT             0.81436         0.89262
            Daily MWT           <.0001          <.0001


              Spearman Correlation Coefficients, N = 95
                      Prob > |r| under H0: Rho=0

                              Logistic          Linear
                                 Model           Model
                                 Water           Water
                                  Temp            Temp

            WaterT             0.82052         0.82052
            Daily MWT           <.0001          <.0001
```

Table 24. Comparison of Pearson (least squares) and Spearman (rank) correlation coefficients for observed versus estimated (from logistic and linear models) daily mean water temperature for air/water temperature relationships for validation data years in the Stamp River: warming season (top); cooling season (bottom). Spearman analyses indicate equal predictive power between the two model types.

```
--------- Site=Sproat Dataset=Validation Season=Warming ---------

           Pearson Correlation Coefficients, N = 49
                  Prob > |r| under H0: Rho=0

                            Logistic          Linear
                               Model           Model
                               Water           Water
                                Temp            Temp

            WaterT           0.77909         0.77999
            Daily MWT         <.0001          <.0001

           Spearman Correlation Coefficients, N = 49
                  Prob > |r| under H0: Rho=0

                            Logistic          Linear
                               Model           Model
                               Water           Water
                                Temp            Temp

            WaterT           0.77960         0.77960
            Daily MWT         <.0001          <.0001

--------- Site=Sproat Dataset=Validation Season=Cooling ---------

           Pearson Correlation Coefficients, N = 16
                  Prob > |r| under H0: Rho=0

                            Logistic          Linear
                               Model           Model
                               Water           Water
                                Temp            Temp

            WaterT           0.85509         0.85852
            Daily MWT         <.0001          <.0001

           Spearman Correlation Coefficients, N = 16
                  Prob > |r| under H0: Rho=0

                            Logistic          Linear
                               Model           Model
                               Water           Water
                                Temp            Temp

            WaterT           0.69118         0.69118
            Daily MWT         0.0030          0.0030
```

Table 25. Comparison of Pearson (least squares) and Spearman (rank) correlation coefficients for observed versus estimated (from logistic and linear models) daily mean water temperature for air/water temperature relationships for validation data years in the Sproat River: warming season (top); cooling season (bottom). Spearman analyses indicate equal predictive power between the two model types.

Decadal Mean Monthly MAT Peaks > 20c

Site: Robertson Creek Air

	Years in Decade	Mean No. Days			Mean Annual Total
		Jul	Aug	Sep	
Decade					
1920s	10	3.9	4.1	0.3	8.3
1930s	10	5.3	7.1	1.0	13.4
1940s	10	4.3	2.9	0.2	7.4
1950s	10	4.7	2.3	0.4	7.4
1960s	10	7.0	4.9	0.7	12.6
1970s	10	7.0	7.1	0.5	14.6
1980s	10	5.9	5.9	0.9	12.7
1990s	10	8.7	9.1	1.3	19.1
2000s	13	9.4	8.9	0.7	19.0

Annual Frequency & Mean Duration (days) for POT20c Events

	POT Event Duration (days)				
	N	Min	Avg	Max	Std
Decade					
1920s	40	1	2.2	8	1.9
1930s	57	1	2.7	9	1.8
1940s	41	1	1.9	8	1.5
1950s	40	0	2.1	9	1.7
1960s	60	1	2.7	11	2.3
1970s	57	0	3.0	20	3.2
1980s	59	1	2.9	17	2.8
1990s	72	1	3.1	16	2.8
2000s	88	1	3.4	17	2.9
Total	514	0	2.8	20	2.5

Table 26. Frequency analysis of decadal mean number of dates per summer month in which regional air temperature exceeded 20°C (top); mean length (days) and mean frequency of number of periods in which regional air temperature continuously exceeded 20°C in Jul-Sep, by decade (bottom).

Decadal Mean Monthly MWT Peaks > 19c

Site: Stamp River

	Years in Decade	Mean No. Days			Mean Annual Total
		Jul	Aug	Sep	
Decade					
1920s	10	8.0	4.1		12.1
1930s	10	8.4	8.1	0.4	16.9
1940s	10	6.6	3.3	0.5	10.4
1950s	10	7.1	2.0		9.1
1960s	10	9.9	8.0	0.6	18.5
1970s	10	11.5	8.7	0.2	20.4
1980s	10	9.2	8.6	1.5	19.3
1990s	10	14.3	11.2	1.8	27.3
2000s	13	16.7	12.3	0.6	29.6

Annual Frequency & Mean Duration (days) for POT19c Events

	POT Event Duration (days)				
	N	Min	Avg	Max	Std
Decade					
1920s	19	0	6.8	20	4.3
1930s	30	1	6.4	23	5.3
1940s	20	0	5.7	32	7.0
1950s	20	0	5.3	30	6.5
1960s	29	0	7.9	41	7.7
1970s	25	0	8.4	29	7.9
1980s	27	1	8.3	24	5.8
1990s	31	1	9.5	39	7.9
2000s	47	1	9.3	49	8.2
Total	248	0	7.8	49	7.1

Table 27. Frequency analysis of decadal mean number of dates per summer month in which estimated mean water temperature in the Stamp River exceeded 19°C (top); mean length (days) and mean frequency of number of periods in which estimated mean water temperature in the Stamp River continuously exceeded 19°C in Jul-Sep, by decade (bottom).

Decadal Mean Monthly MWT Peaks > 20c

Site: Sproat River

	Years in Decade	Mean No. Days			Mean Annual Total
		Jul	Aug	Sep	
Decade					
1920s	10	20.4	21.7	4.7	46.8
1930s	10	17.4	23.4	7.7	48.5
1940s	10	14.3	16.4	3.1	33.8
1950s	10	14.9	12.3	2.5	29.7
1960s	10	21.0	18.4	4.1	43.5
1970s	10	17.8	21.0	4.7	43.5
1980s	10	18.1	25.6	6.0	49.7
1990s	10	25.4	25.6	12.2	63.2
2000s	13	27.9	26.5	7.5	61.9

Annual Frequency & Mean Duration (days) for POT20c Events

	POT Event Duration (days)				
	N	Min	Avg	Max	Std
Decade					
1920s	33	1	15.7	50	13.7
1930s	41	1	13.7	49	13.2
1940s	36	1	10.2	39	8.9
1950s	32	0	10.5	47	10.1
1960s	30	1	16.9	87	21.2
1970s	35	0	13.4	50	12.6
1980s	35	1	10.1	55	14.3
1990s	37	1	19.3	83	20.2
2000s	47	1	19.9	93	20.0
Total	326	0	15.2	93	15.8

Table 28. Frequency analysis of decadal mean number of dates per summer month in which estimated mean water temperature in the Sproat River exceeded 20°C (top); mean length (days) and mean frequency of number of periods in which estimated mean water temperature in the Sproat River continuously exceeded 20°C in Jul-Sep, by decade (bottom).

Decadal Mean Monthly Flow < 24 cms

Site: Stamp River

	Years in Decade	Mean No. Days				Mean Annual Total
		Jun	Jul	Aug	Sep	
Decade						
1910s	7		3.1	11.1	19.1	33.4
1920s	10	0.3	8.7	25.2	20.9	55.1
1940s	10		6.2	21.5	18.6	46.3
1950s	10		3.3	13.7	17.8	34.8
1960s	10			1.1	0.6	1.7
1970s	10			1.4	0.1	1.5
1980s	10		1.8	12.0	14.3	28.1
1990s	10	2.2	9.4	18.1	14.8	44.5
2000s	13		0.4	5.2	6.2	11.8

Annual Frequency & Mean Duration (days) for POT < 24 cms Events

	POT Event Duration (days)				
	N	Min	Avg	Max	Std
Decade					
1910s	8	1	29.0	83	25.2
1920s	13	3	42.2	95	29.4
1940s	14	1	33.1	79	29.5
1950s	11	3	31.6	75	21.1
1960s	3	1	5.7	11	5.0
1970s	2	1	7.5	14	9.2
1980s	17	1	16.5	67	22.8
1990s	25	1	17.8	78	19.6
2000s	13	1	11.7	38	11.7
Total	106	1	23.6	95	24.2

Table 29. Frequency analysis of decadal mean number of dates per summer month in which daily mean flow in the Stamp River was less than 24 cms (top); mean length (days) and mean frequency of number of periods in which daily mean flow in the Stamp River continuously remained below 24 cms, by decade (bottom). Note: 1930s omitted due to insufficient data.

Decadal Mean Monthly Flow > 90 cms

Site: Stamp River

	Years in Decade	Mean No. Days				Mean Annual Total
		Jun	Jul	Aug	Sep	
Decade						
1910s	7	15.7	5.9			21.6
1920s	10	8.7	1.4		1.9	12.0
1940s	10	6.5	0.5		0.4	7.4
1950s	10	14.6	2.8		0.7	18.1
1960s	10	12.1	0.9		1.1	14.1
1970s	10	10.9	4.4	0.7	2.3	18.3
1980s	10	5.7	0.3			6.0
1990s	10	5.7	2.8	1.0	0.7	10.2
2000s	13	2.4				2.4

Annual Frequency & Mean Duration (days) for POT > 90 cms Events

	POT Event Duration (days)				
	N	Min	Avg	Max	Std
Decade					
1910s	8	2	18.9	48	17.1
1920s	10	1	12.0	43	15.1
1940s	8	1	9.5	27	9.5
1950s	13	1	14.2	36	11.8
1960s	18	1	7.9	23	8.3
1970s	18	1	9.5	53	12.0
Total	75	1	11.3	53	12.1

Table 30. Frequency analysis of decadal mean number of dates per summer month in which daily mean flow in the Stamp River was greater than 90 cms (top); mean length (days) and mean frequency of number of periods in which daily mean flow in the Stamp River continuously exceeded 90 cms, by decade (bottom). Note: 1930s omitted due to insufficient data.

Decadal Mean Monthly Flow < 5 cms

Site: Sproat River

	Years in Decade	Mean No. Days				Mean Annual Total
		Jun	Jul	Aug	Sep	
Decade						
1910s	7			2.0	7.6	9.6
1920s	10		0.8	7.7	12.5	21.0
1940s	10		0.1	6.3	7.9	14.3
1950s	10		0.5	5.3	4.9	10.7
1960s	10		1.4	12.9	11.5	25.8
1970s	10		4.5	13.3	9.1	26.9
1980s	10		2.3	21.9	25.0	49.2
1990s	10	1.1	8.5	22.0	21.0	52.6
2000s	13		3.2	15.6	17.5	36.2

Annual Frequency & Mean Duration (days) for POT < 5 cms Events

	POT Event Duration (days)				
	N	Min	Avg	Max	Std
Decade					
1910s	4	1	16.5	43	19.4
1920s	9	2	23.0	59	19.9
1940s	5	8	28.6	54	17.9
1950s	3	9	35.7	51	23.2
1960s	14	1	18.4	75	20.6
1970s	10	1	26.9	57	21.6
1980s	12	1	41.0	77	25.8
1990s	9	10	58.7	103	29.8
2000s	12	5	39.4	62	22.0
Total	78	1	32.6	103	25.2

Table 31. Frequency analysis of decadal mean number of dates per summer month in which daily mean flow in the Sproat River was less than 5 cms (top); mean length (days) and mean frequency of number of periods in which daily mean flow in the Sproat River continuously remained below 5 cms, by decade (bottom). Note: 1930s omitted due to insufficient data.

FIGURES

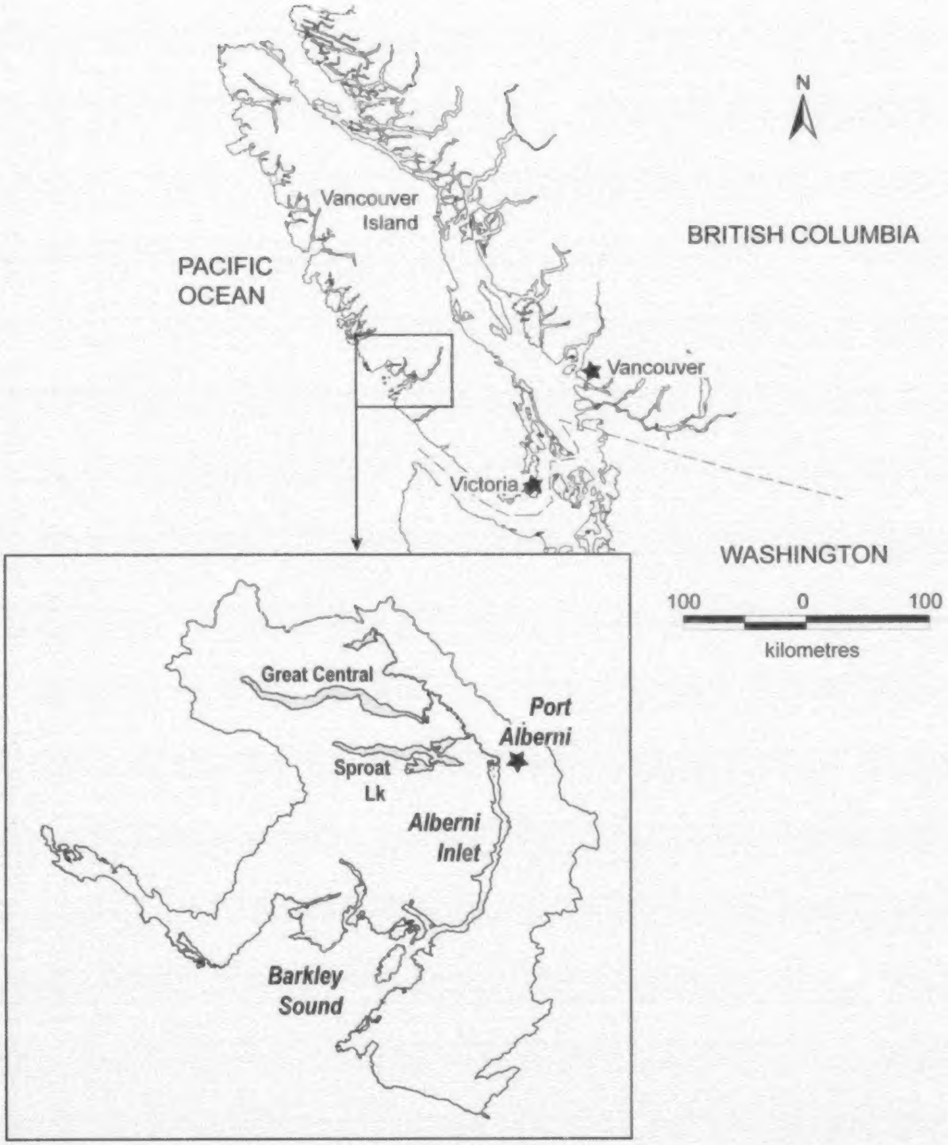

N
Vancouver Island
BRITISH COLUMBIA
PACIFIC OCEAN
Vancouver
Victoria
WASHINGTON
100
0
100
kilometres
Great Central
Port Alberni
Sproat Lk
Alberni Inlet
Barkley Sound

Figure 1. Somass watershed and Alberni Inlet, west coast of Vancouver Island, British Columbia.

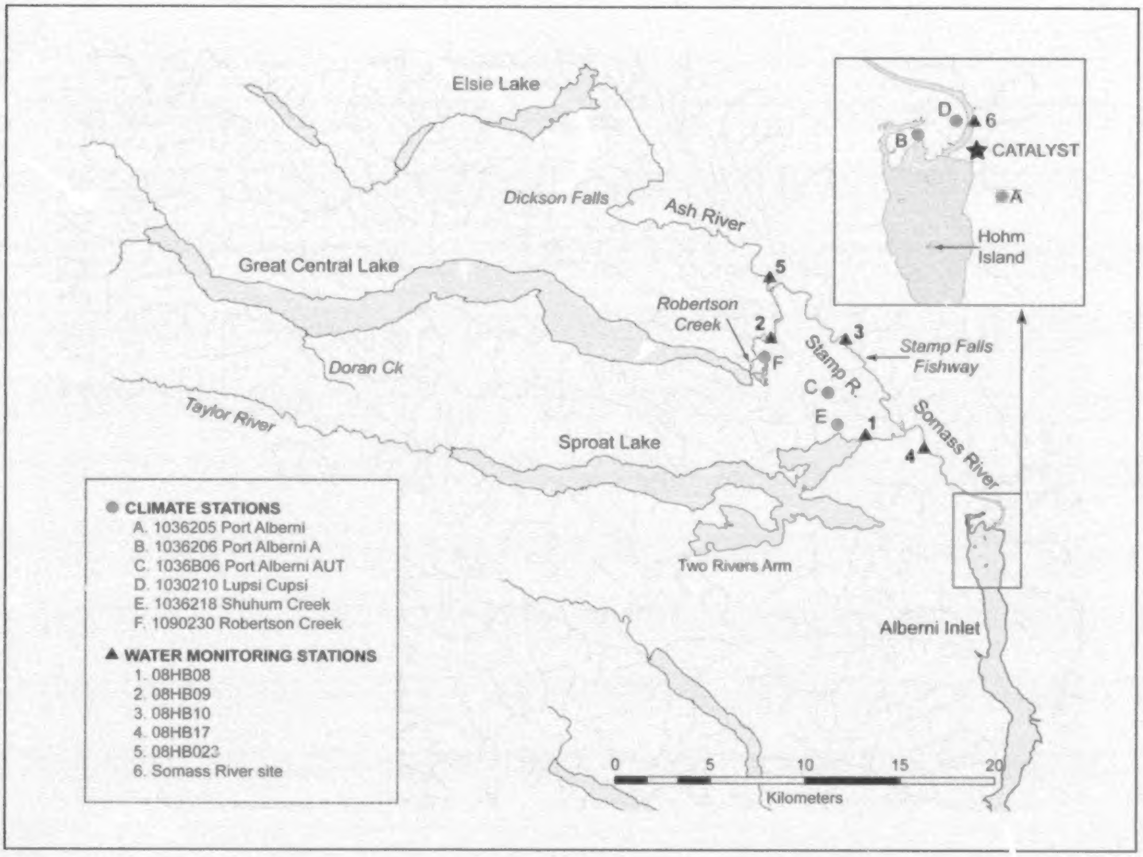
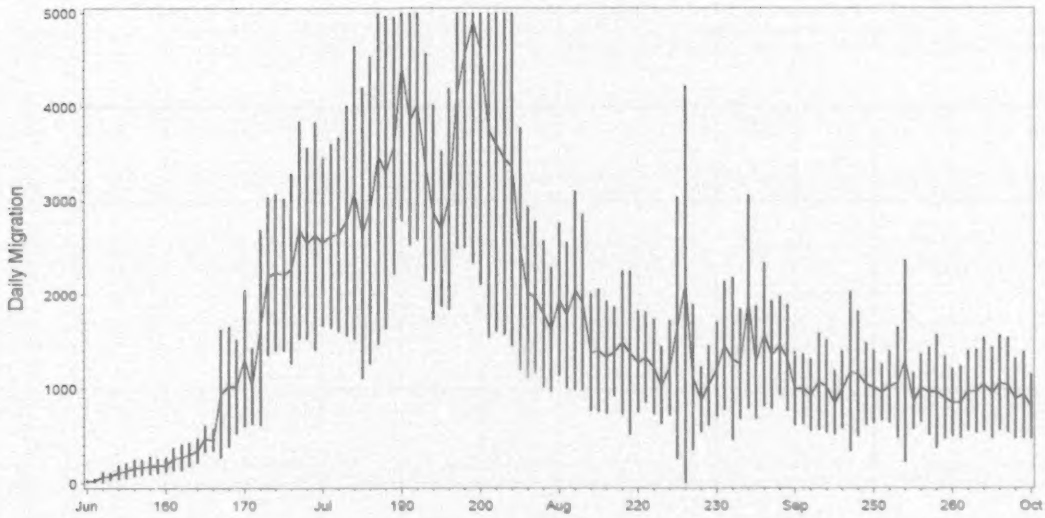

Elsie Lake
Dickson Falls
Ash River
Great Central Lake
5
Robertson Creek
2
F
3
Stamp R.
Stamp Falls Fishway
Doran Ck
C
E
1
Taylor River
Sproat Lake
Somass River
4
Two Rivers Arm
Alberni Inlet
D
6
B
CATALYST
A
Hohm Island
● CLIMATE STATIONS
A. 1036205 Port Alberni
B. 1036206 Port Alberni A
C. 1036B06 Port Alberni AUT
D. 1030210 Lupsi Cupsi
E. 1036218 Shuhum Creek
F. 1090230 Robertson Creek
▲ WATER MONITORING STATIONS
1. 08HB08
2. 08HB09
3. 08HB10
4. 08HB17
5. 08HB023
6. Somass River site
0
5
10
15
20
Kilometers

Figure 2. Somass watershed with key Environment Canada climate stations and Canadian Hydrographic Survey water monitoring stations.



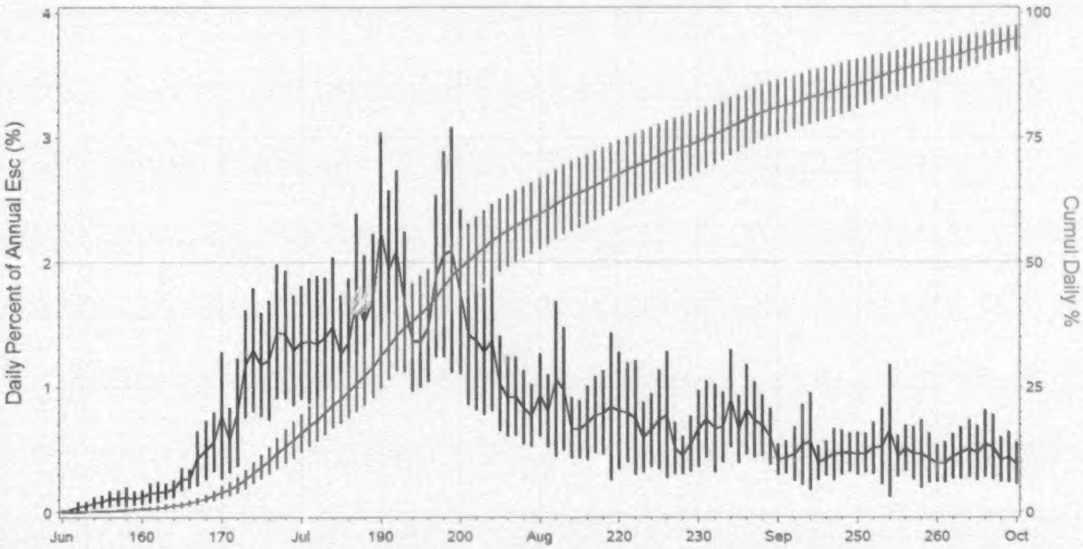


Figure 3. Great Central Lake sockeye migration timing (1976-2012). Mean daily migration ± 2 standard errors (top); mean daily migration rate (as a percent (%) of annual stock escapement (black line) and mean cumulative daily migration ± 2 standard errors (blue line) (bottom). TT50% ~ day 202. See APPENDIX for annual plots.

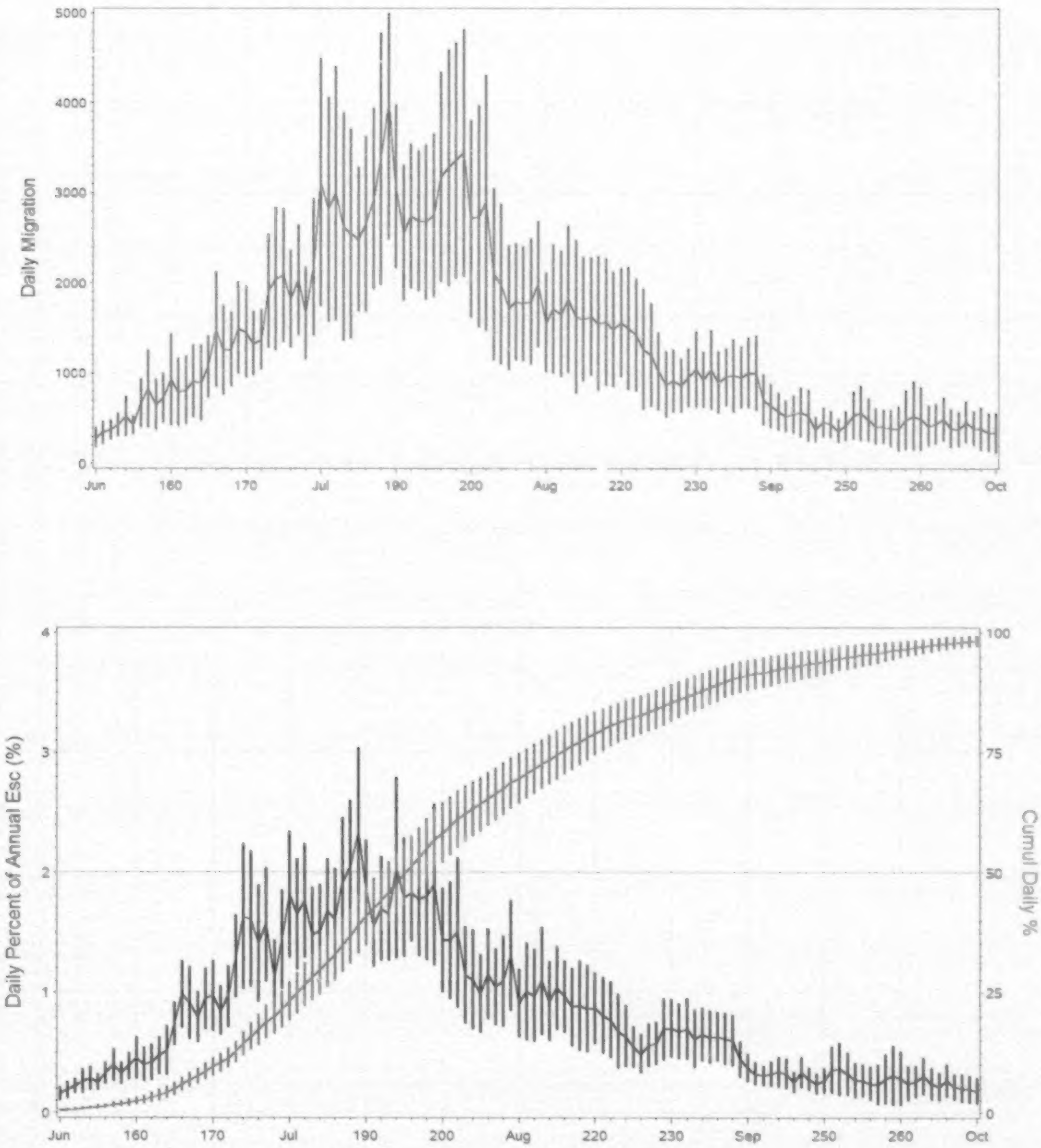


Figure 4. Sproat Lake sockeye migration timing (1974-2012). Mean daily migration ± 2 standard errors (top); mean daily migration rate (as a percent (%) of annual stock escapement (black line) and mean cumulative daily migration ± 2 standard errors (blue line) (bottom). TT50% ~ day 195. See APPENDIX for annual plots.

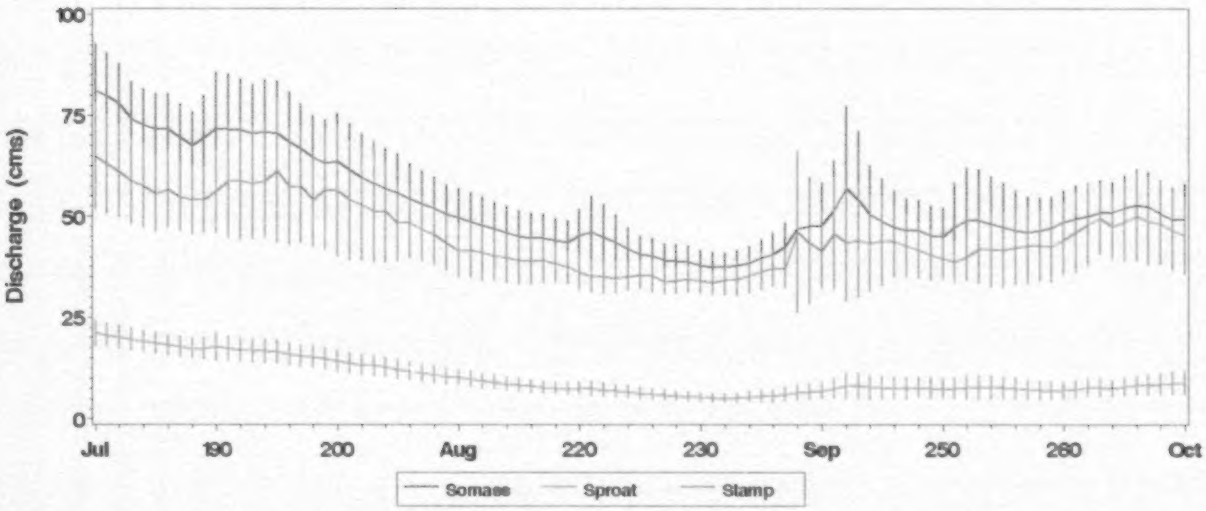


Figure 5. Observed daily mean discharge (cms) ± 2 standard errors of the mean for summer months (July-September) for the Somass River (WSC Station 08HB017; 1960-2002), Sproat River (WSC Station 08HB008; 1960-2012), and Stamp River (WSC Station 08HB010; 1960-1978).

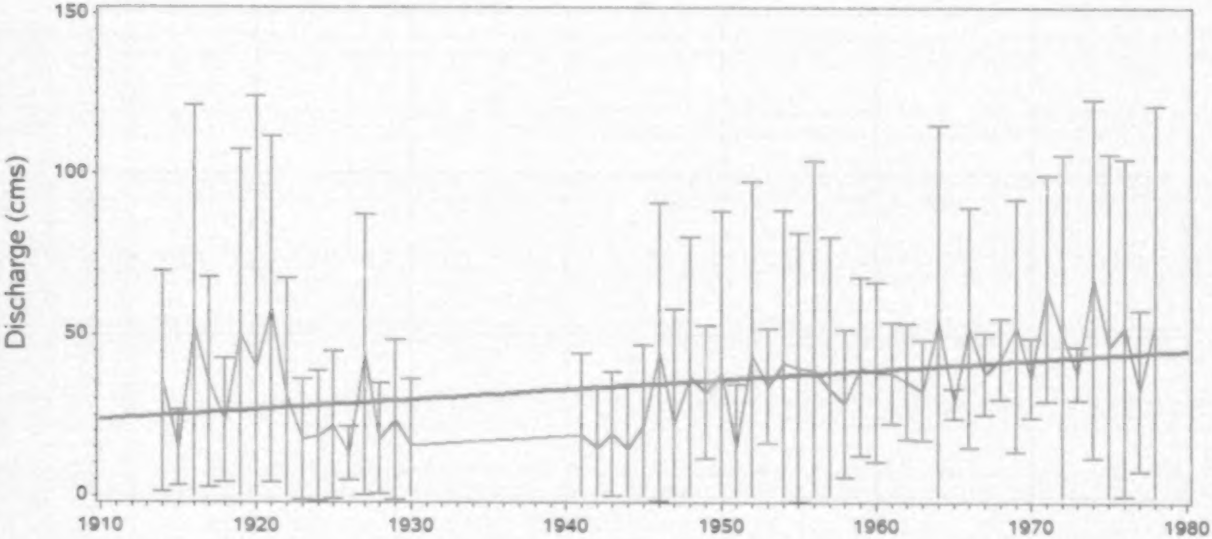


Figure 6. Trend in mean summer (July-September) discharge (cms) observed at Stamp River (WSC Station 08HB010; 1914-1978).

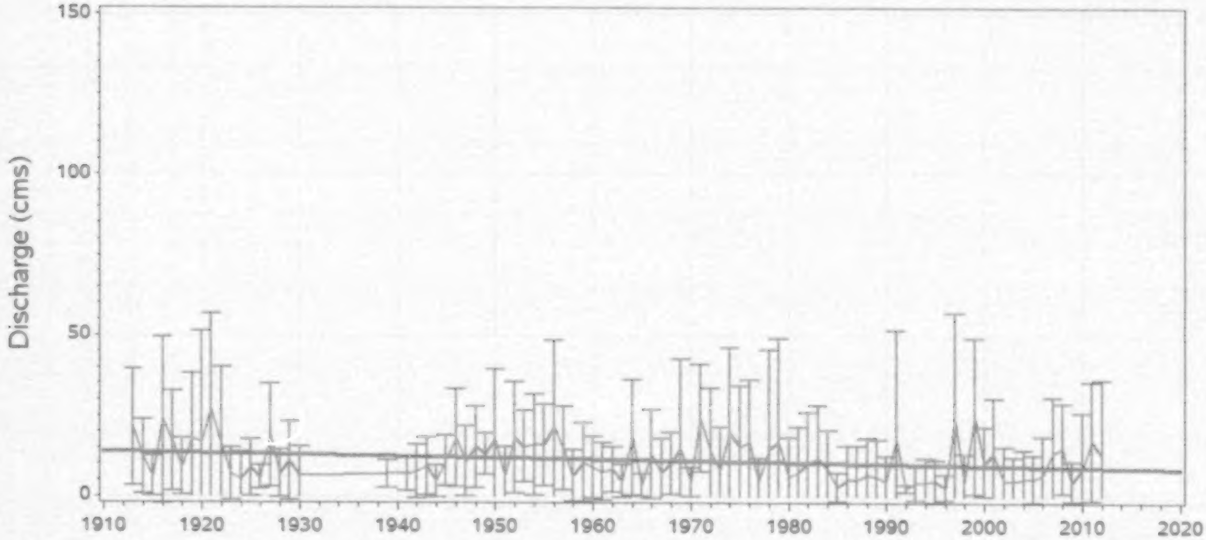


Figure 7. Trend in mean summer (July-September) discharge (cms) observed at Sproat River (WSC Station 08HB008; 1913-2012).

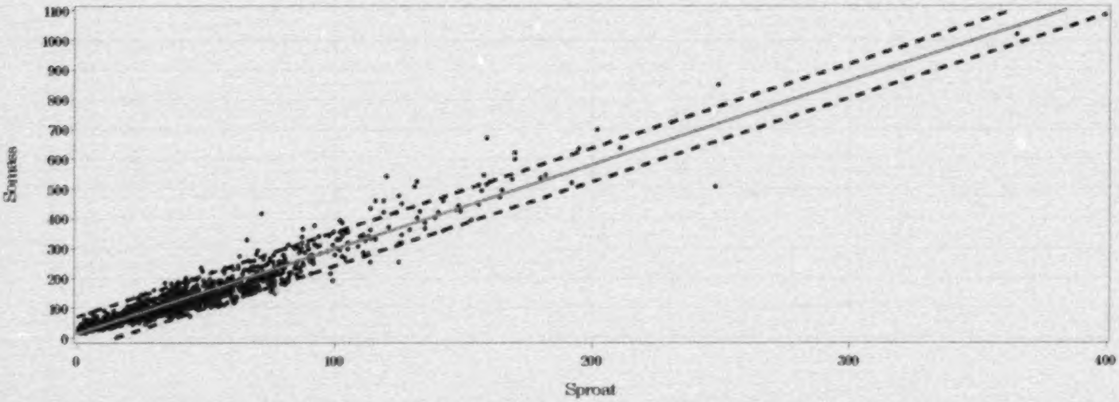
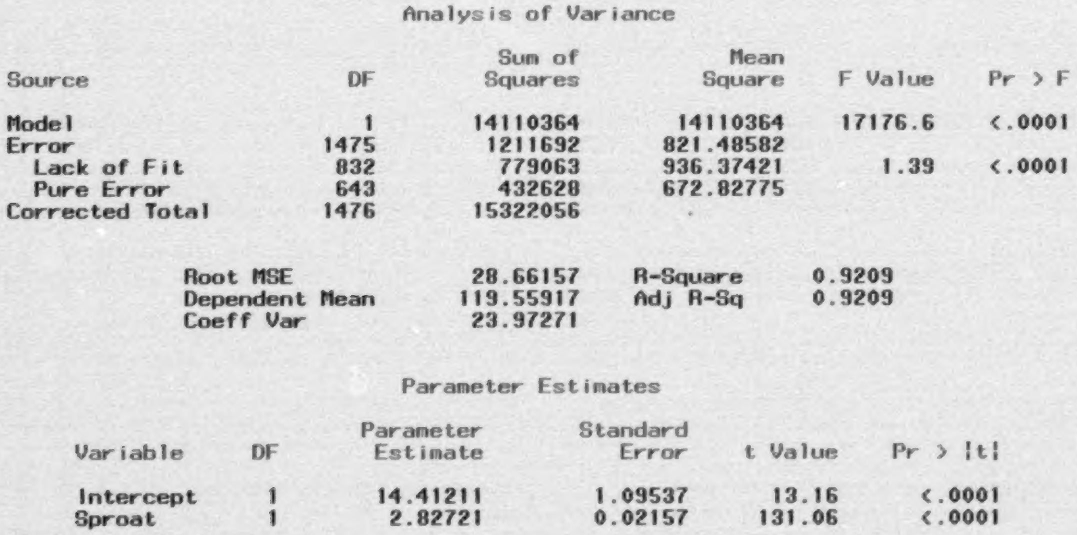


Figure 8. Daily mean discharge (cms) at the Somass River (WSC Station 08HB017) as a linear function of Sproat River daily mean discharge (08HB008), based on calibration data (10^{th}, 20^{th}, and 30^{th} observation sub-sampled from Jan-Dec data), 1960-2012.



```
                              Analysis of Variance

                                       Sum of           Mean
Source                    DF          Squares         Square    F Value    Pr > F

Model                      1         14110364       14110364    17176.6    <.0001
Error                   1475          1211692      821.48582
  Lack of Fit            832           779063      936.37421       1.39    <.0001
  Pure Error             643           432628      672.82775
Corrected Total         1476         15322056              .

            Root MSE               28.66157    R-Square     0.9209
            Dependent Mean        119.55917    Adj R-Sq     0.9209
            Coeff Var              23.97271

                              Parameter Estimates

                           Parameter       Standard
       Variable     DF      Estimate          Error    t Value    Pr > |t|

       Intercept     1      14.41211        1.09537      13.16      <.0001
       Sproat        1       2.82721        0.02157     131.06      <.0001
```

Figure 9. Daily mean discharge (cms) at the Somass River (WSC Station 08HB017) as a linear function of Sproat River daily mean discharge (08HB008), based on calibration data (10^{th}, 20^{th}, and 30^{th} observation sub-sampled from Jan-Dec data), 1960-2012.

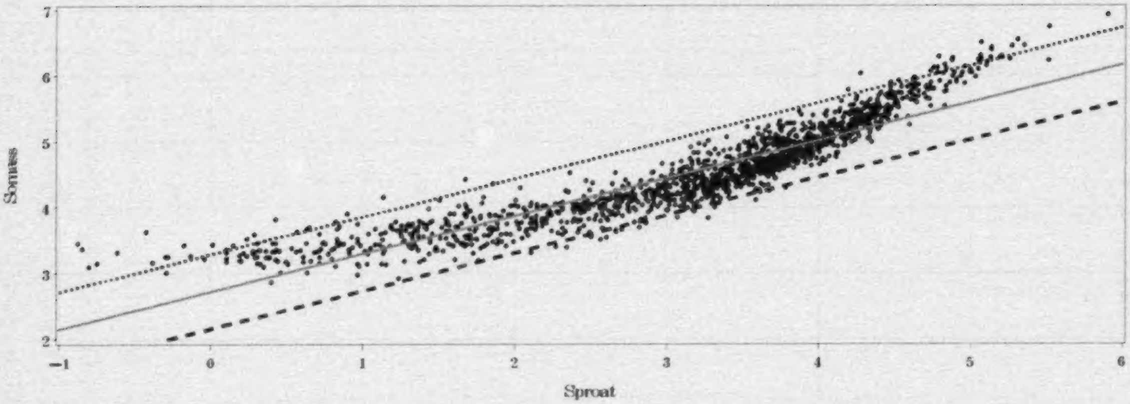
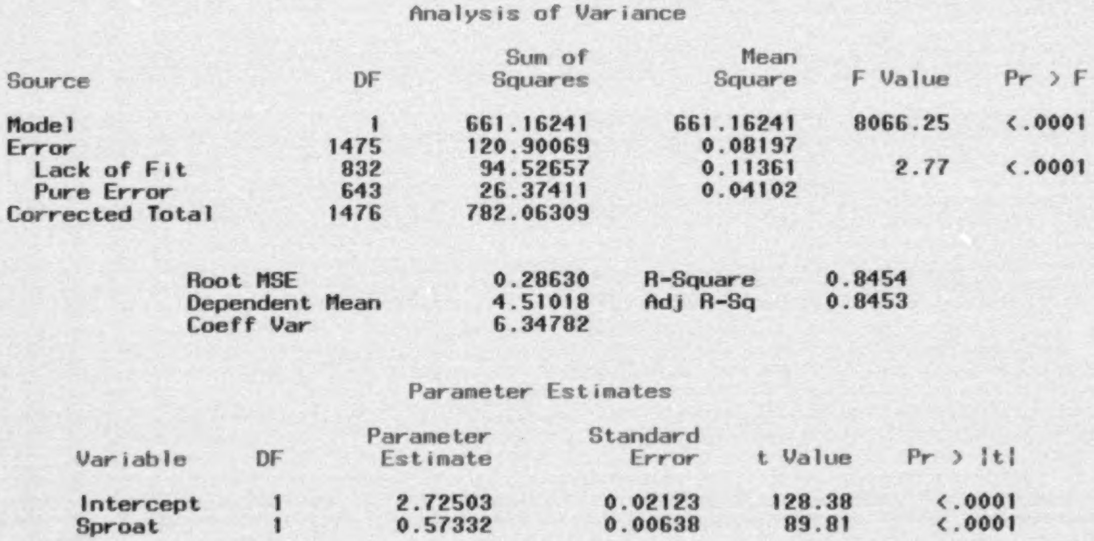


Figure 10. Daily mean discharge (cms) at the Somass River (WSC Station 08HB017) as a log function of Sproat River daily mean discharge (08HB008), based on calibration data (10th, 20th, and 30th observation sub-sampled from Jan-Dec data) 1960-2012.



```
                              Analysis of Variance

                                      Sum of           Mean
Source                     DF        Squares         Square    F Value    Pr > F

Model                       1      661.16241      661.16241    8066.25    <.0001
Error                    1475      120.90069        0.08197
  Lack of Fit             832       94.52657        0.11361       2.77    <.0001
  Pure Error              643       26.37411        0.04102
Corrected Total          1476      782.06309


            Root MSE                 0.28630    R-Square     0.8454
            Dependent Mean           4.51018    Adj R-Sq     0.8453
            Coeff Var                6.34782


                              Parameter Estimates

                         Parameter       Standard
Variable       DF         Estimate          Error    t Value    Pr > |t|

Intercept       1          2.72503        0.02123     128.38      <.0001
Sproat          1          0.57332        0.00638      89.81      <.0001
```

Figure 11. Daily mean discharge (cms) at the Somass River (WSC Station 08HB017) as a log function of Sproat River daily mean discharge (08HB008), based on calibration data (10th, 20th, and 30th observation sub-sampled from Jan-Dec data) 1960-2012.

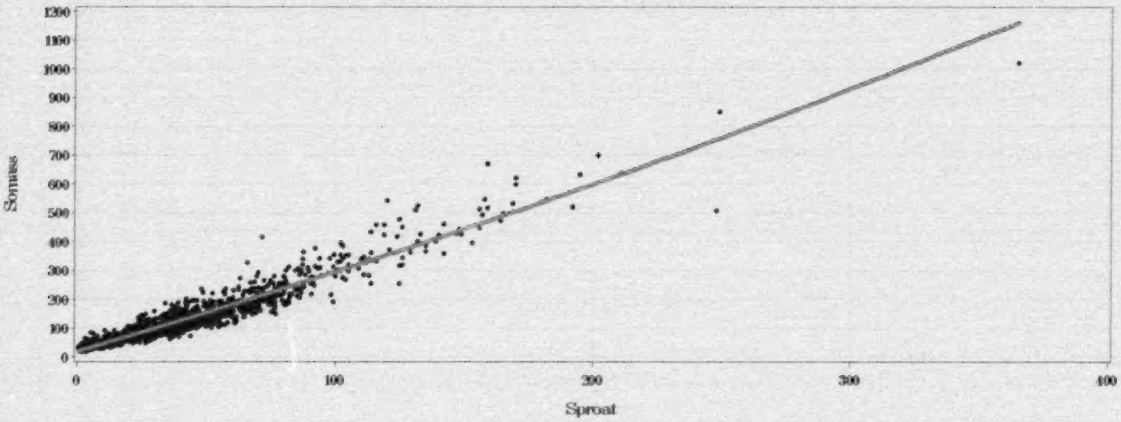
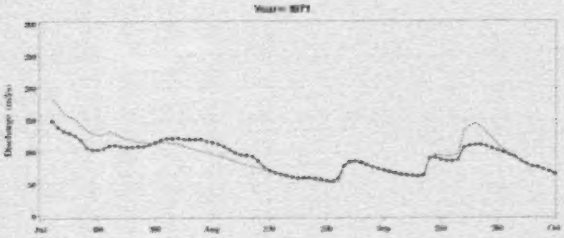
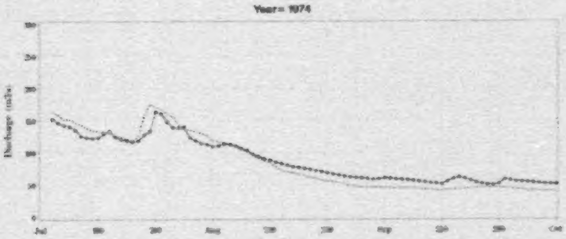


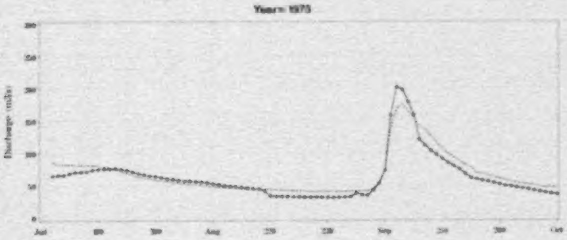
Figure 12. Daily mean discharge (cms) at the Somass River (WSC 08HB017) as a curvilinear function of Sproat River daily mean discharge (08HB008), based on calibration data (10th, 20th, and 30th observation sub-sampled from Jan-Dec data), 1960-2012.

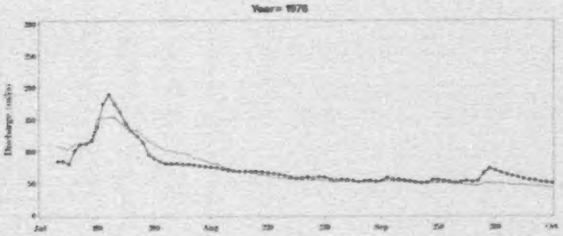
```
                                Sum of        Mean               Approx
Source                  DF     Squares      Square    F Value    Pr > F

Model                    2    14138172     7069086    8801.40    <.0001
Error                 1474     1183884       803.2
Corrected Total       1476    15322056

                                 Approx
      Parameter     Estimate    Std Error    Approximate 95% Confidence Limits

      a              18.7081       1.3062       16.1459       21.2703
      b               2.6140       0.0421        2.5315        2.6965
      c              0.00141     0.000240      0.000940       0.00188
```

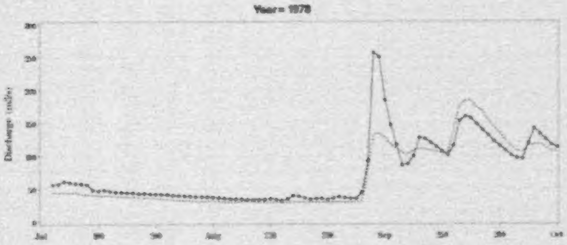
Figure 13. Daily mean discharge (cms) at the Somass River (WSC 08HB017) as a curvilinear function of Sproat River daily mean discharge (08HB008), based on calibration data (10th, 20th, and 30th observation sub-sampled from Jan-Dec data), 1960-2012.

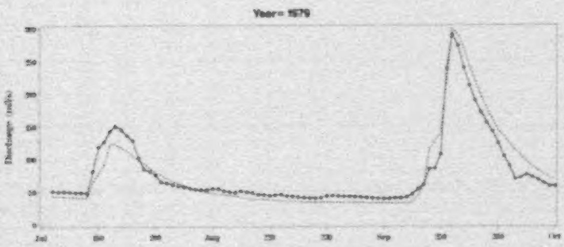

Year= 1971

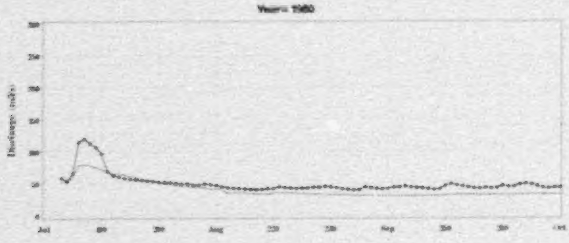

Year= 1974

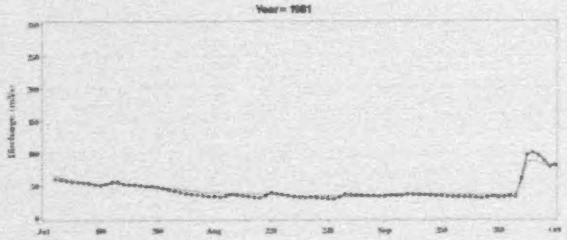

Year= 1975

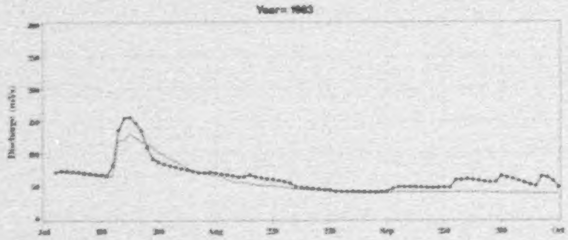

Year= 1976

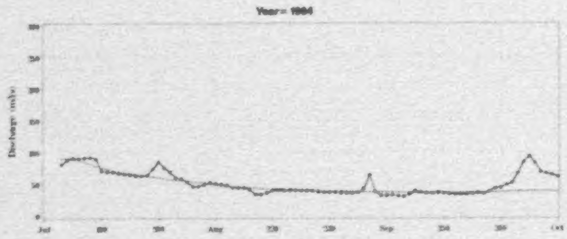

Year= 1978

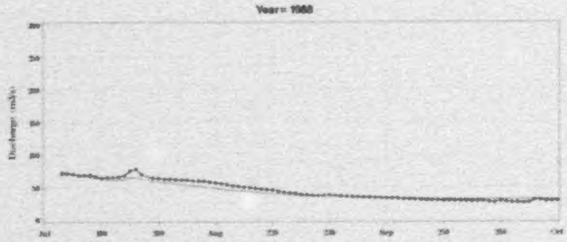

Year= 1979

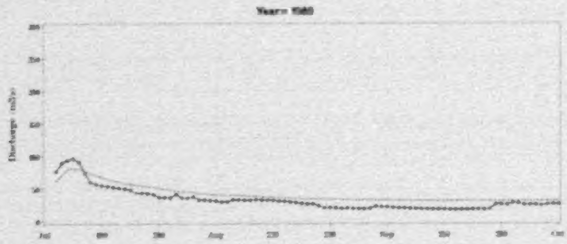

Year= 1980


Year= 1981


Year= 1983


Year= 1984


Year= 1985


Year= 1986

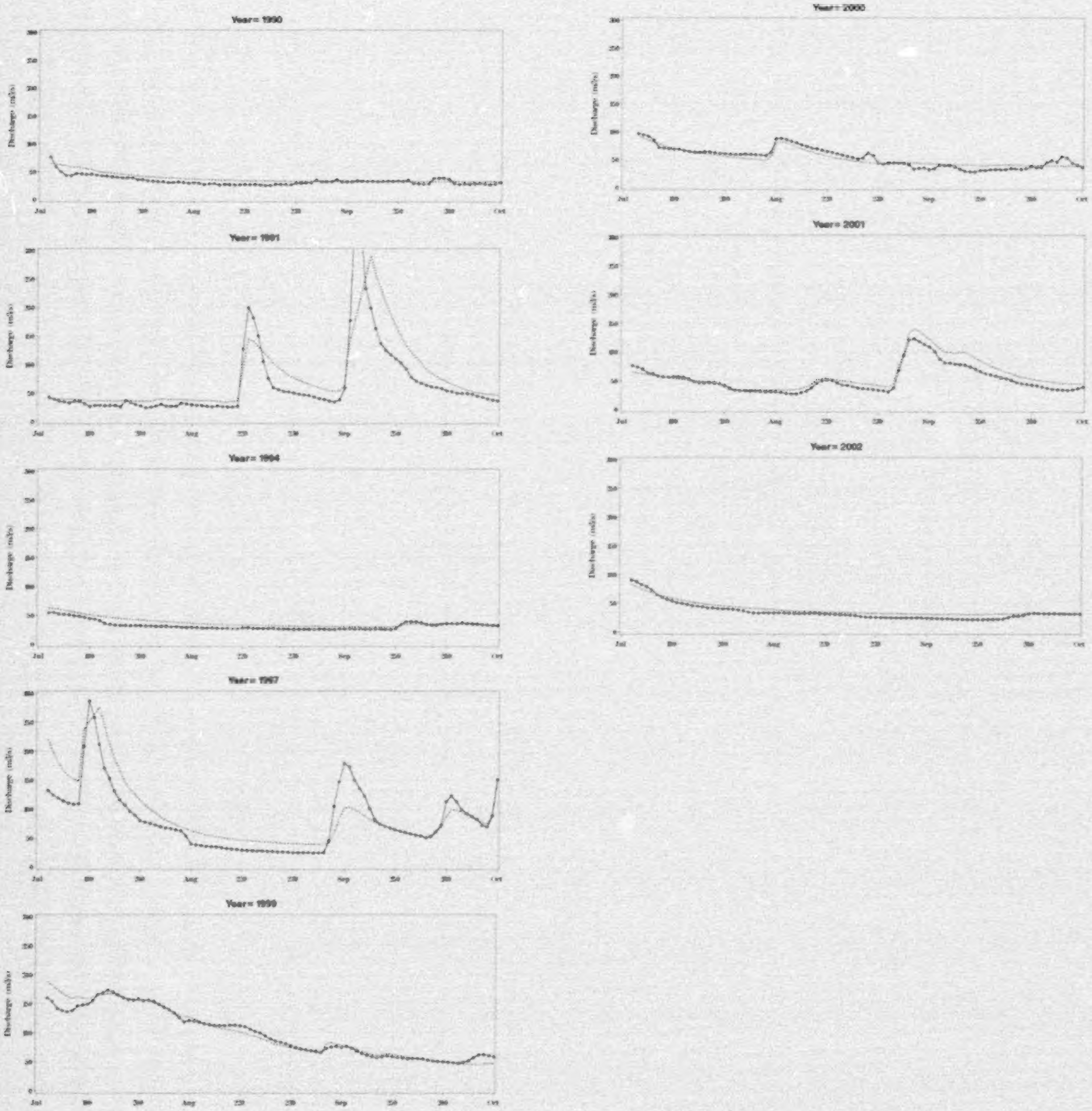


Figure 14. Observed (solid line) and estimated (dashed line) daily mean discharge (cms) in the Somass River for a subsample of years. Estimated Somass discharge is derived from Sproat River daily mean discharge (WSC Station 08HB008) based on a curvilinear function (SOMASS = A +BX + CX^{2}; see Figure 12 and Figure 13), 1960-2012.

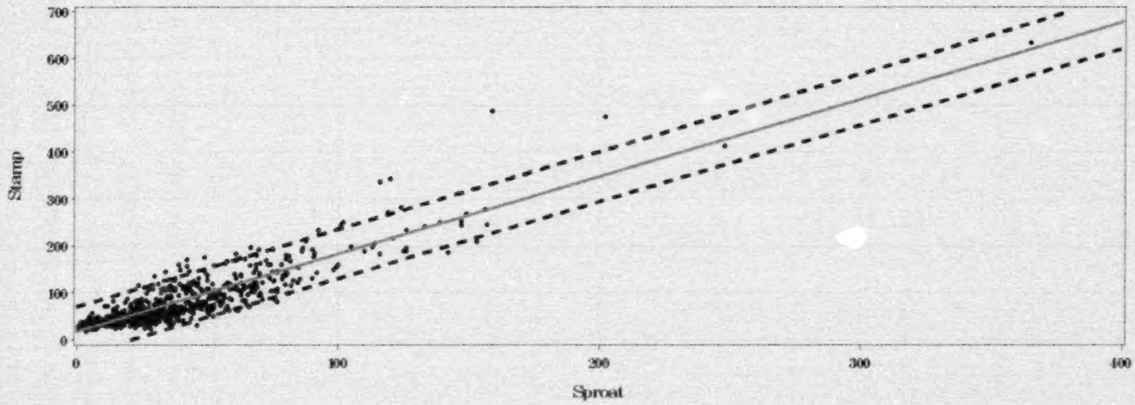
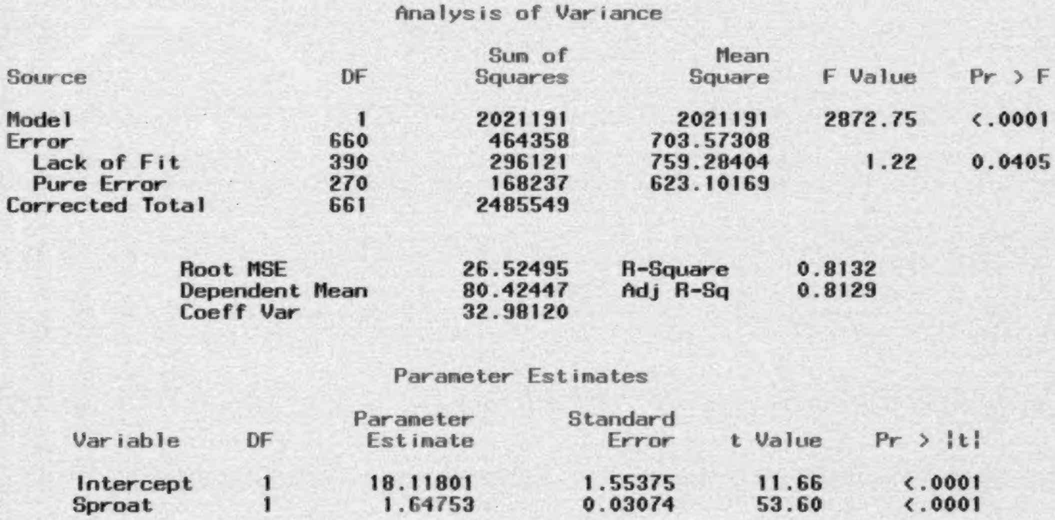


Figure 15. Daily mean discharge (cms) at the Stamp River (WSC Station 08HB010) as a linear function of Sproat River daily mean discharge (08HB008), based on calibration data (10th, 20th, and 30th observation sub-sampled from Jan-Dec data) 1960-2012.



```
                              Analysis of Variance

                                      Sum of           Mean
Source                   DF          Squares         Square    F Value    Pr > F

Model                     1          2021191        2021191    2872.75    <.0001
Error                   660           464358      703.57308
  Lack of Fit           390           296121      759.28404       1.22    0.0405
  Pure Error            270           168237      623.10169
Corrected Total         661          2485549

             Root MSE               26.52495    R-Square     0.8132
             Dependent Mean         80.42447    Adj R-Sq     0.8129
             Coeff Var              32.98120

                              Parameter Estimates

                           Parameter       Standard
   Variable      DF         Estimate          Error    t Value    Pr > |t|

   Intercept      1         18.11801        1.55375      11.66      <.0001
   Sproat         1          1.64753        0.03074      53.60      <.0001
```

Figure 16. Daily mean discharge (cms) at the Stamp River (WSC Station 08HB010) as a linear function of Sproat River daily mean discharge (08HB008), based on calibration data (10th, 20th, and 30th observation sub-sampled from Jan-Dec data) 1960-2012.

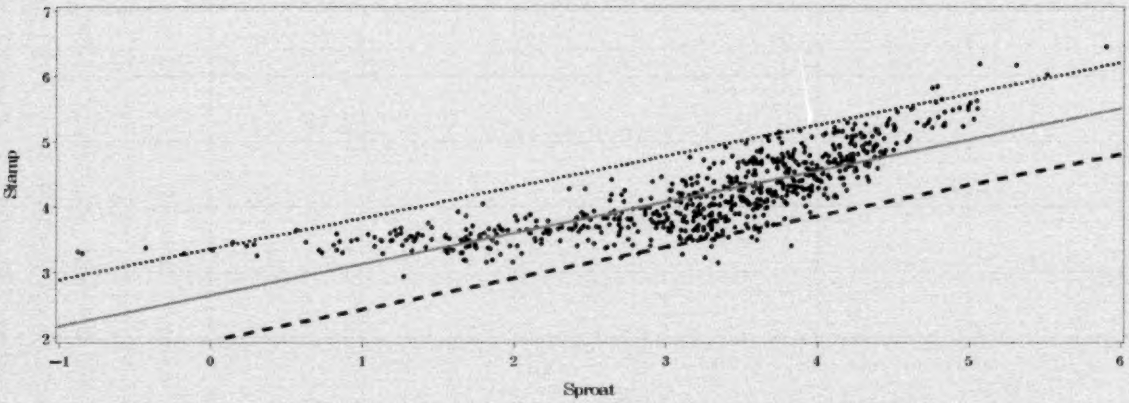


Figure 17. Daily mean discharge (cms) at the Stamp River (WSC Station 08HB010) as a log function of Sproat River daily mean discharge (08HB008), based on calibration data (10th, 20th, and 30th observation sub-sampled from Jan-Dec data) 1960-2012.

```
                              Analysis of Variance

                                     Sum of           Mean
Source                    DF        Squares         Square    F Value    Pr > F

Model                      1      156.61390      156.61390    1251.35    <.0001
Error                    660       82.60261        0.12516
  Lack of Fit            390       58.63947        0.15036       1.69    <.0001
  Pure Error             270       23.96314        0.08875
Corrected Total          661      239.21651

             Root MSE              0.35377    R-Square     0.6547
             Dependent Mean        4.18804    Adj R-Sq     0.6542
             Coeff Var             8.44722

                              Parameter Estimates

                           Parameter       Standard
    Variable      DF        Estimate          Error    t Value    Pr > |t|

    Intercept      1         2.65449        0.04548      58.37      <.0001
    Sproat         1         0.47522        0.01343      35.37      <.0001
```

Figure 18. Daily mean discharge (cms) at the Stamp River (WSC Station 08HB010) as a log function of Sproat River daily mean discharge (08HB008), based on calibration data (10th, 20th, and 30th observation sub-sampled from Jan-Dec data), 1960-2012.

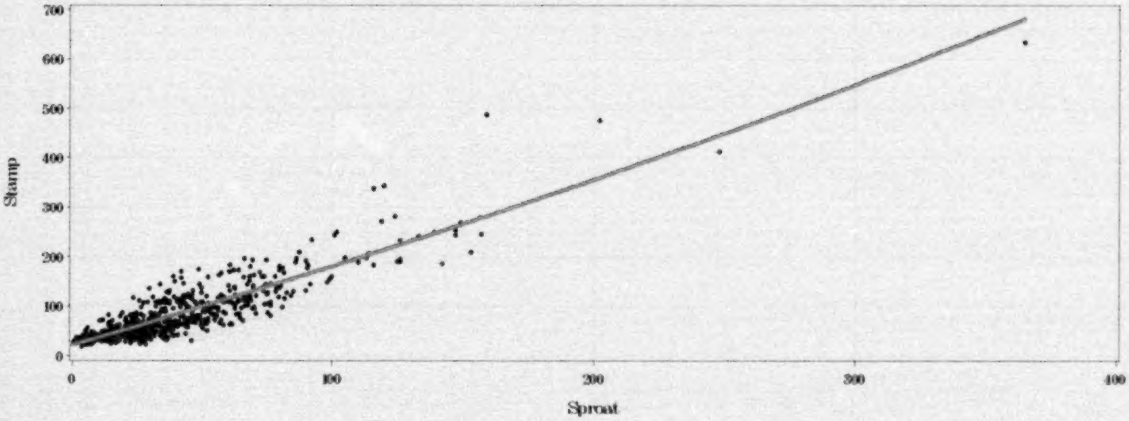
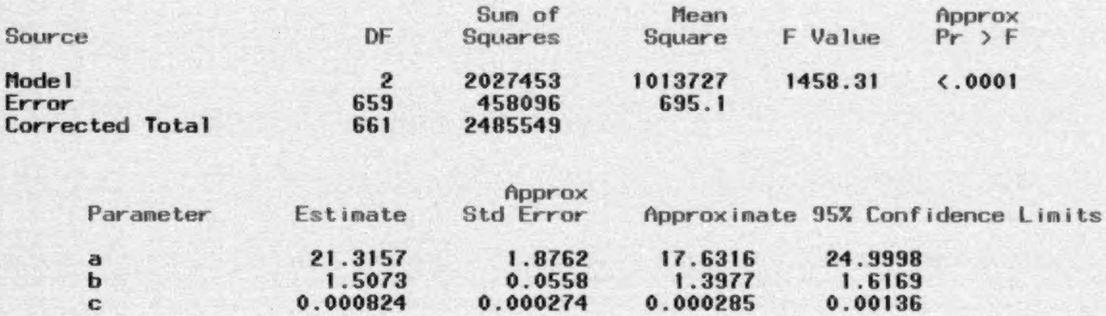


Figure 19. Daily mean discharge (cms) at the Stamp River (WSC 08HB010) as a curvilinear function of Sproat River daily mean discharge (08HB008), based on calibration data (10th, 20th, and 30th observation sub-sampled from Jan-Dec data), 1960-2012.



```
                                  Sum of        Mean                 Approx
Source                    DF     Squares      Square    F Value    Pr > F

Model                      2     2027453     1013727    1458.31    <.0001
Error                    659      458096       695.1
Corrected Total          661     2485549

                                  Approx
      Parameter    Estimate    Std Error    Approximate 95% Confidence Limits

      a             21.3157       1.8762      17.6316      24.9998
      b              1.5073       0.0558       1.3977       1.6169
      c            0.000824     0.000274     0.000285      0.00136
```

Figure 20. Daily mean discharge (cms) at the Stamp River (WSC 08HB010) as a curvilinear function of Sproat River daily mean discharge (08HB008), based on calibration data (10th, 20th, and 30th observation sub-sampled from Jan-Dec data), 1960-2012.

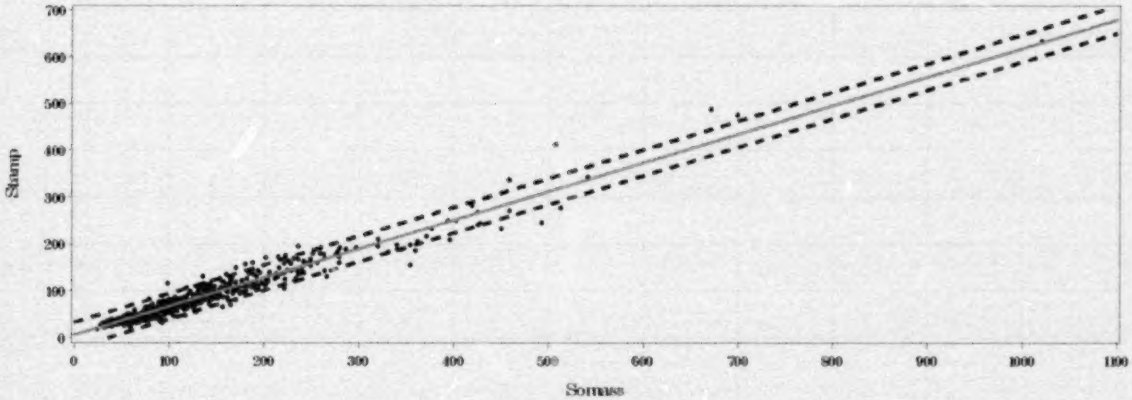
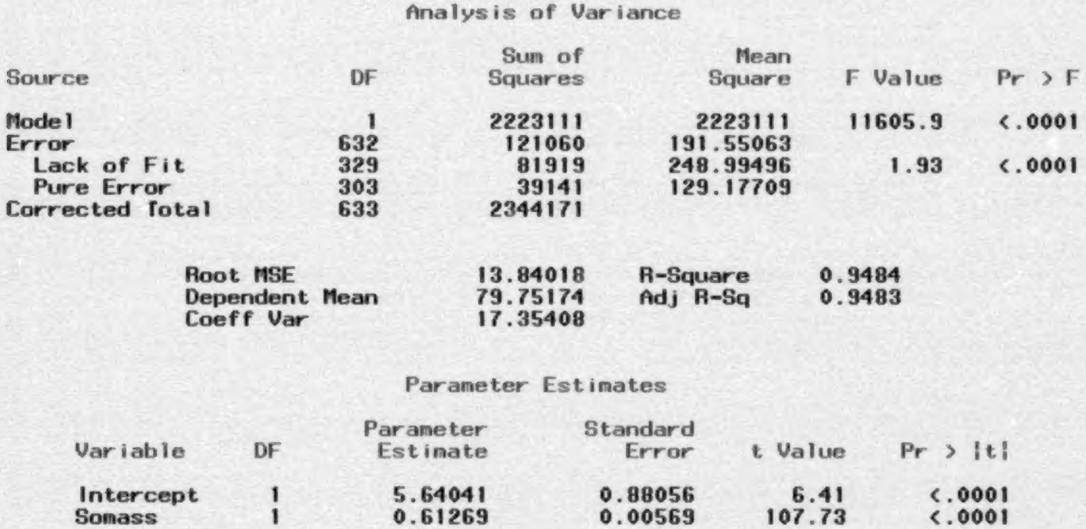


Figure 21. Daily mean discharge (cms) at the Stamp River (WSC Station 08HB010) as a linear function of Somass River daily mean discharge (08HB017), based on calibration data (10th, 20th, and 30th observation sub-sampled from Jan-Dec data), 1960-2012.



```
                              Analysis of Variance

                                        Sum of           Mean
Source                    DF           Squares         Square    F Value    Pr > F

Model                      1           2223111        2223111    11605.9    <.0001
Error                    632            121060      191.55063
  Lack of Fit            329             81919      248.99496       1.93    <.0001
  Pure Error             303             39141      129.17709
Corrected Total          633           2344171

             Root MSE              13.84018    R-Square     0.9484
             Dependent Mean        79.75174    Adj R-Sq     0.9483
             Coeff Var             17.35408

                              Parameter Estimates

                           Parameter       Standard
     Variable     DF        Estimate          Error    t Value    Pr > |t|

     Intercept     1         5.64041        0.88056       6.41      <.0001
     Somass        1         0.61269        0.00569     107.73      <.0001
```

Figure 22. Daily mean discharge (cms) at the Stamp River (WSC Station 08HB010) as a linear function of Somass River daily mean discharge (08HB017), based on calibration data (10th, 20th, and 30th observation sub-sampled from Jan-Dec data), 1960-2012.

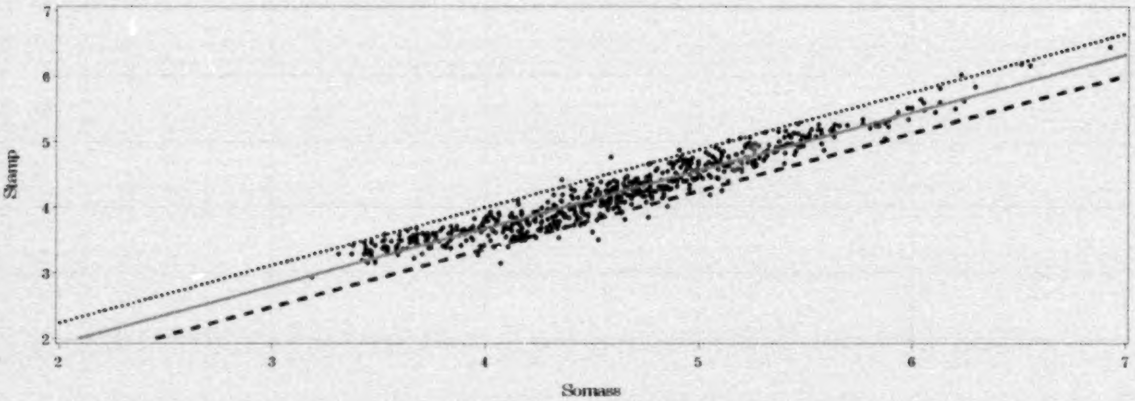


Figure 23. Daily mean discharge (cms) at the Stamp River (WSC Station 08HB010) as a log function of Somass River daily mean discharge (08HB017), based on calibration data (10th, 20th, and 30th observation sub-sampled from Jan-Dec data), 1960-2012.

```
                              Analysis of Variance

                                     Sum of           Mean
Source                   DF         Squares         Square    F Value    Pr > F

Model                     1       208.35371      208.35371    8127.29    <.0001
Error                   632        16.20214        0.02564
  Lack of Fit           329         9.95069        0.03025       1.47    0.0004
  Pure Error            303         6.25145        0.02063
Corrected Total         633       224.55585


             Root MSE              0.16011    R-Square     0.9278
             Dependent Mean        4.18294    Adj R-Sq     0.9277
             Coeff Var             3.82777


                              Parameter Estimates

                           Parameter       Standard
      Variable      DF      Estimate          Error    t Value    Pr > |t|

      Intercept      1       0.14760        0.04521       3.26      0.0012
      Somass         1       0.88284        0.00979      90.15      <.0001
```

Figure 24. Daily mean discharge (cms) at the Stamp River (Station 08HB010) as a log function of Somass River daily mean discharge (08HB017), based on calibration data (10th, 20th, and 30th observation sub-sampled from Jan-Dec data), 1960-2012.

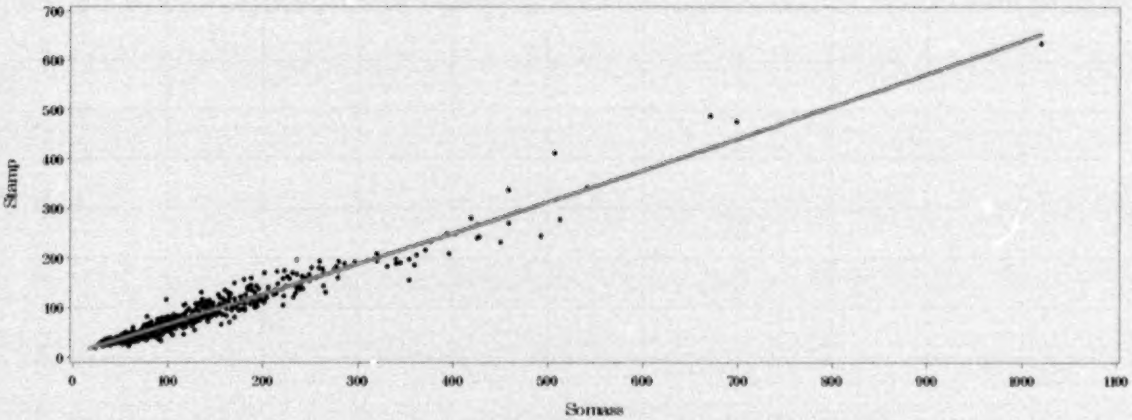


Figure 25. Daily mean discharge (cms) at the Stamp River (Station 08HB010) as a curvilinear function of Somass River daily mean discharge (08HB017), based on calibration data (10th, 20th, and 30th observation sub-sampled from Jan-Dec data), 1960-2012.

```
                                  Sum of         Mean                 Approx
Source                    DF     Squares       Square    F Value    Pr > F

Model                      2     2223991      1111996    5838.51    <.0001
Error                    631      120180        190.5
Corrected Total          633     2344171

                                  Approx
      Parameter      Estimate    Std Error    Approximate 95% Confidence Limits

      a                7.3781       1.1934        5.0346        9.7215
      b                0.5900       0.0120        0.5666        0.6135
      c              0.000042     0.000019      3.616E-6      0.000080
```

Figure 26. Daily mean discharge (cms) at the Stamp River (Station 08HB010) as a curvilinear function of Somass River daily mean discharge (08HB017), based on calibration data (10th, 20th, and 30th observation sub-sampled from Jan-Dec data), 1960-2012.

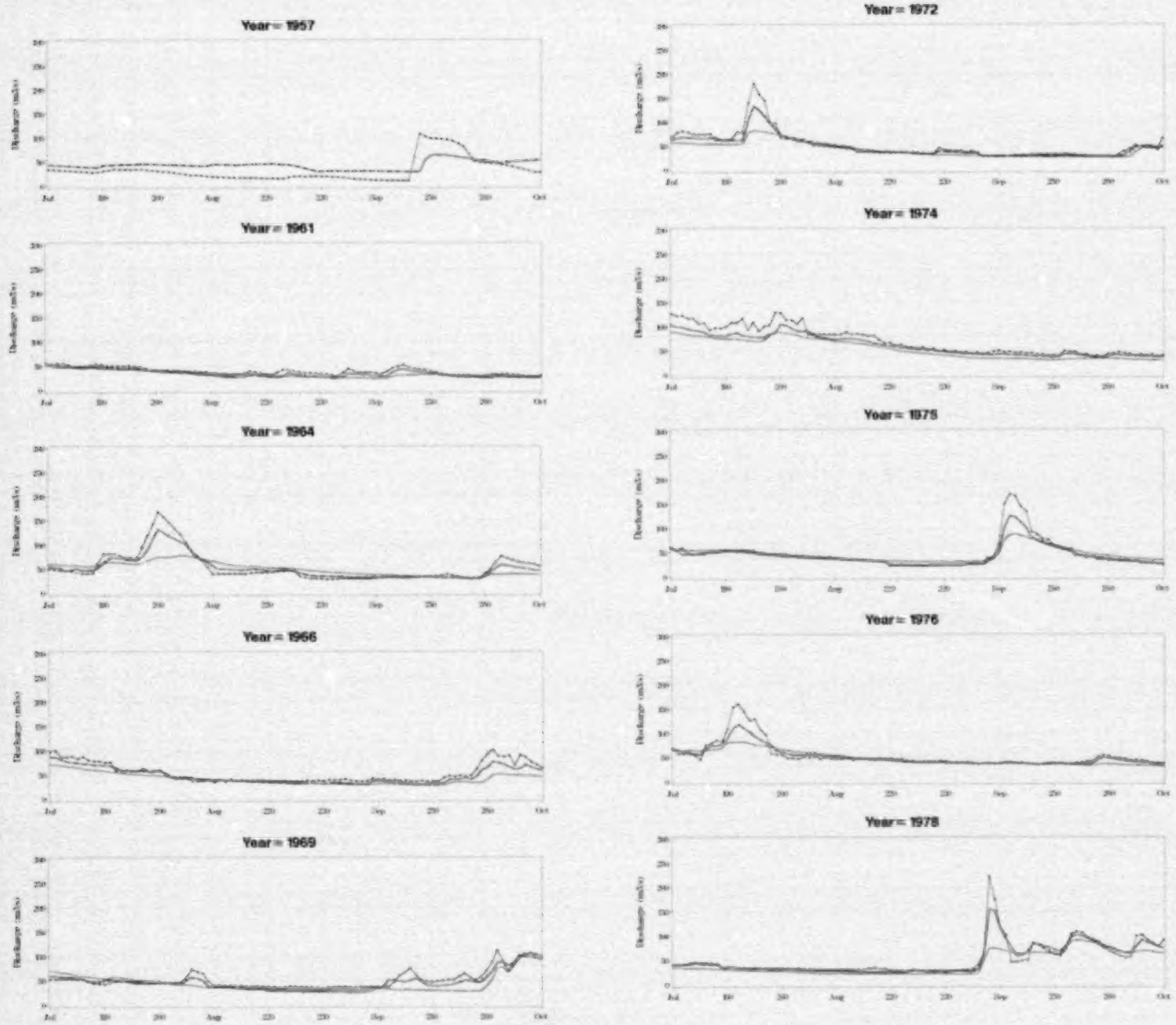


Figure 27. Example years with observed (solid line) and estimated (dashed lines) daily mean discharge (cms) in the Stamp River. Estimated Stamp discharge is derived from observed Somass River daily mean discharge (green) based on a log function or from quadratic function with observed Sproat River discharge (red).

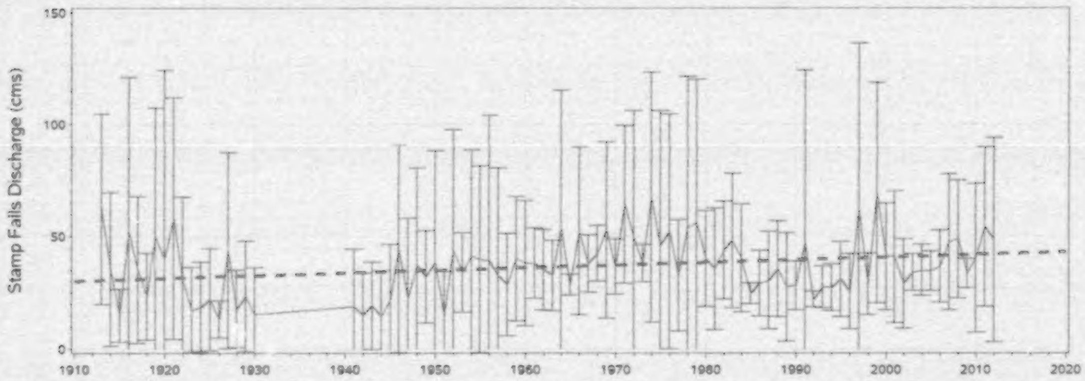


Figure 28. Trend in mean summer (July-September) discharge (cms) at Stamp River (observed: 1914-1978; estimated: 1979-2012).

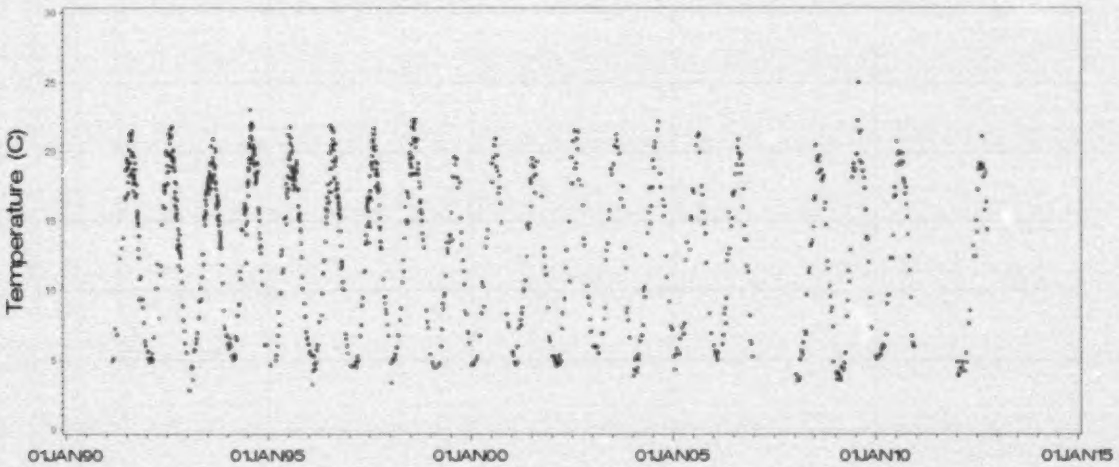


Figure 29. Water temperature data for Somass River watershed reference site at Papermill Dam, 1991-2012 (Source: CATALYST PAPER ENVIRONMENTAL EFFLUENT MONITORING PROGRAM).

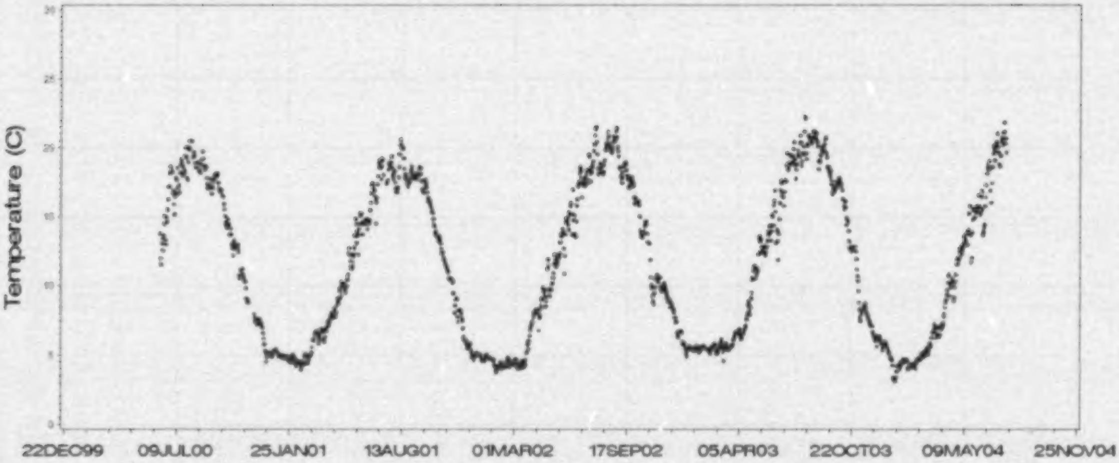


Figure 30. Water temperature data for Stamp River watershed reference site at Stamp Falls Fishway, 1990-1994 (Source: DFO SOUTH COAST).

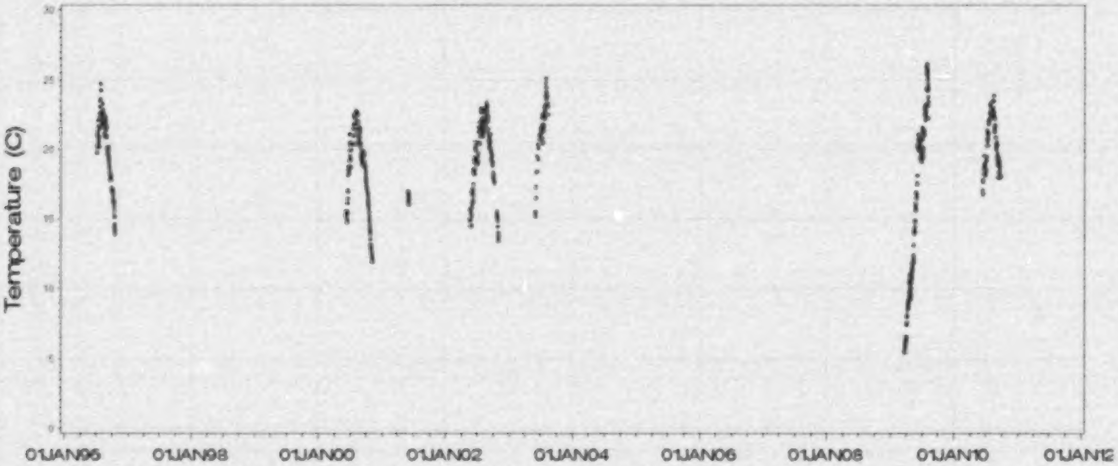


Figure 31. Water temperature data for Sproat River watershed reference site at Sproat Falls Fishway, 1996, 2000-2003 (Source: DFO SALMON IN REGIONAL ECOSYSTEMS and DFO SOUTH COAST), 2009-2010 (Source: BC CONSERVATION FOUNDATION).

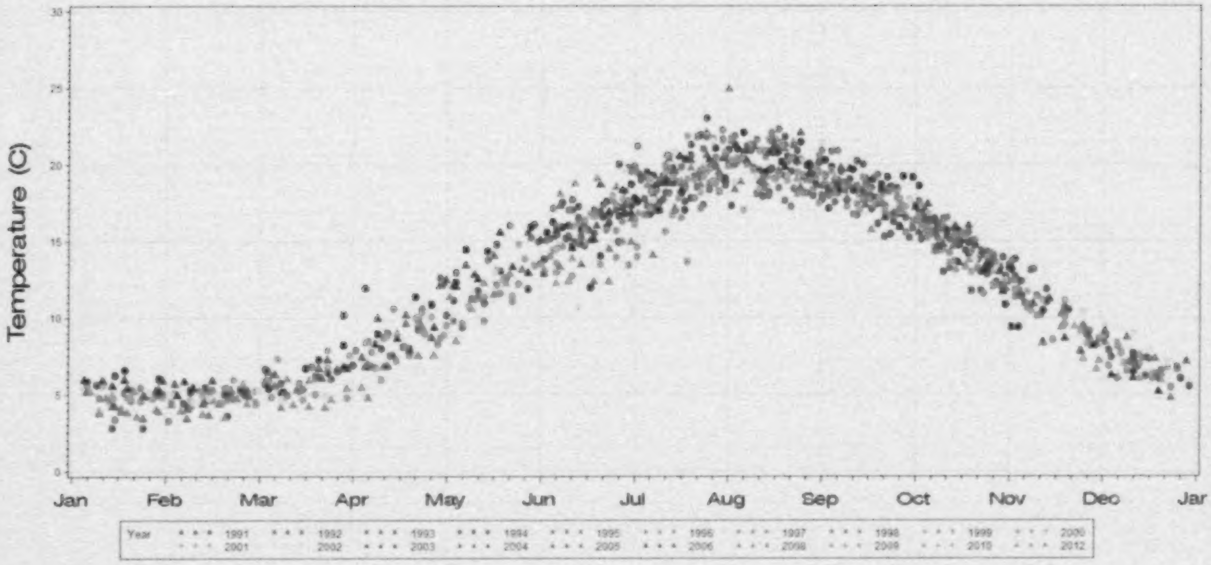


Figure 32. Annual thermograph of water temperature data for Somass River watershed reference site at Papermill Dam, by year, 1991-2012 (Source: CATALYST PAPER ENVIRONMENTAL EFFLUENT MONITORING PROGRAM).

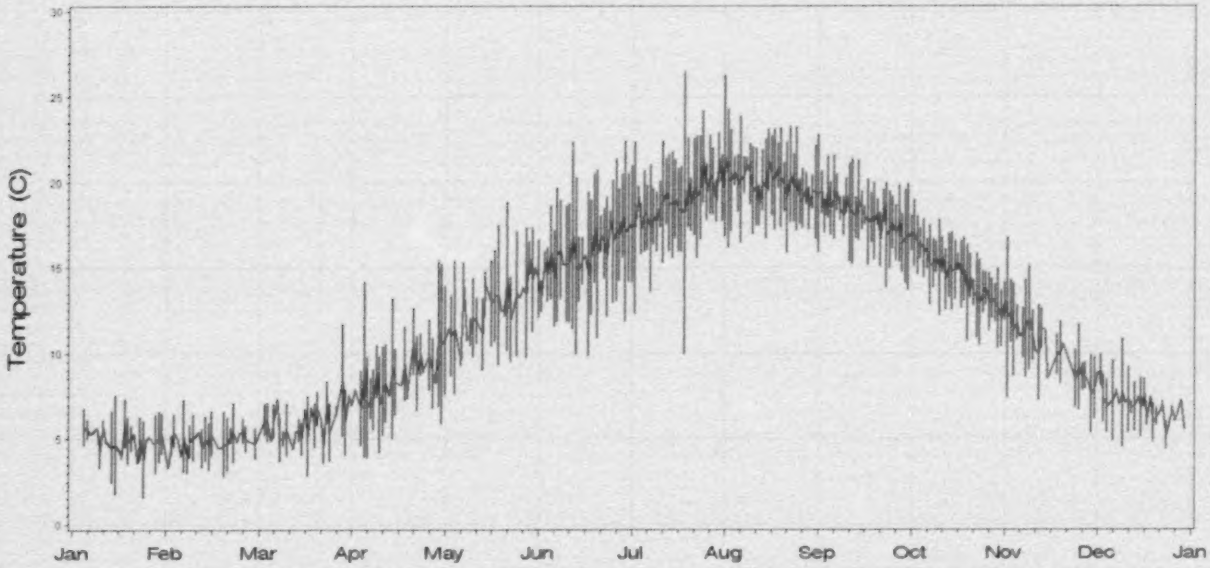


Figure 33. Annual thermograph of water temperature data for Somass River watershed reference site at Papermill Dam, 1991-2012 (Source: CATALYST PAPER ENVIRONMENTAL EFFLUENT MONITORING PROGRAM).

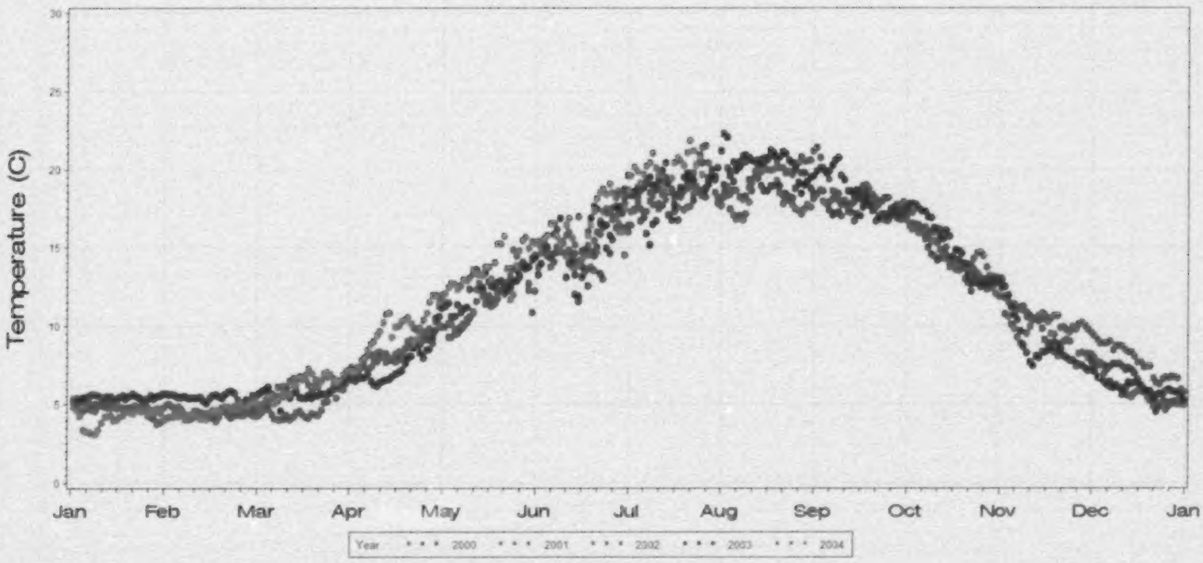


Figure 34. Annual thermograph of mean daily water temperature data for Stamp River watershed reference site at Stamp Falls Fishway, by year, 2000-2004 (Source: DFO SOUTH COAST).

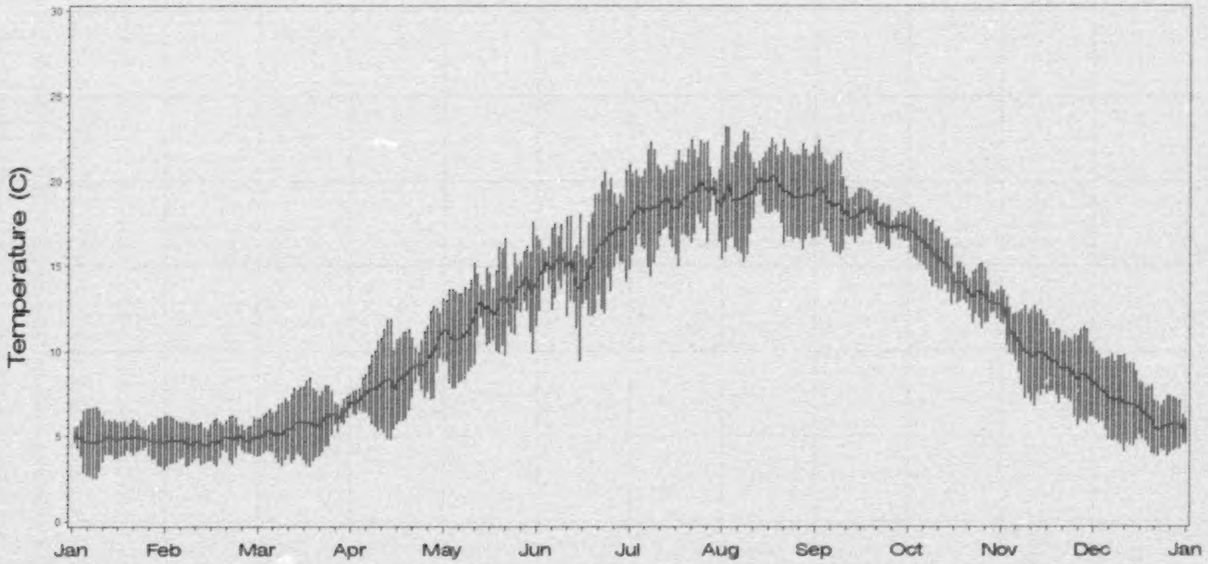


Figure 35. Annual thermograph of mean daily water temperature data ± two standard deviations for Stamp River watershed reference site at Stamp Falls Fishway, 2000-2004 (Source: DFO SOUTH COAST).

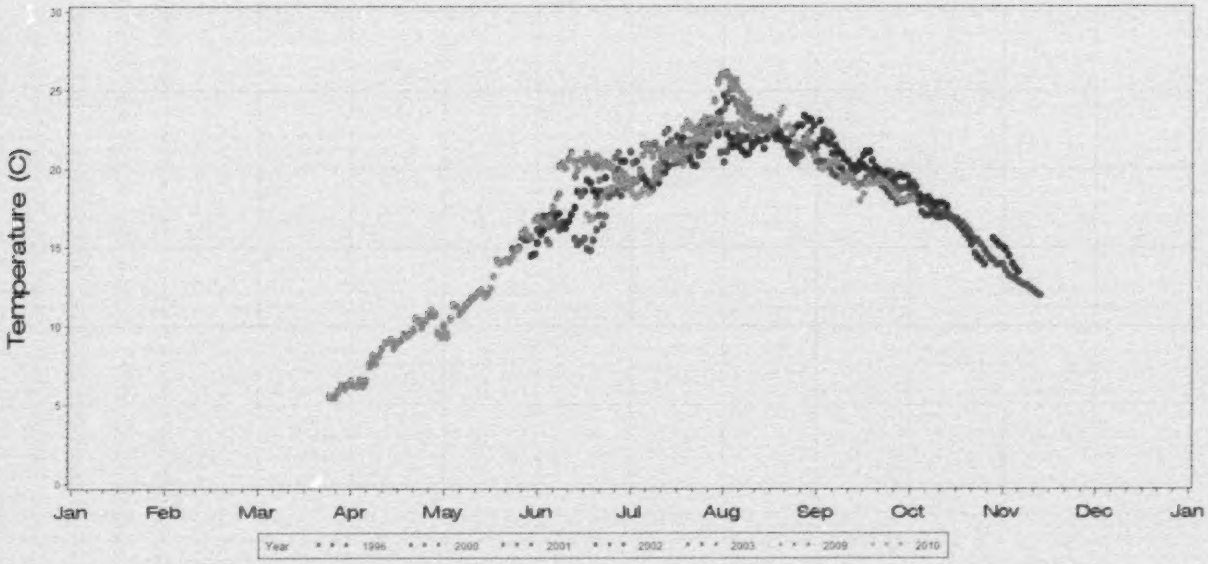


Figure 36. Annual thermograph of mean daily water temperature data for Sproat River watershed reference site at Sproat Falls Fishway, 1996, 2000-2003, (Source: DFO SALMON IN REGIONAL ECOSYSTEMS and DFO SOUTH COAST), by year, 2009-2010 (Source: BC CONSERVATION FOUNDATION).

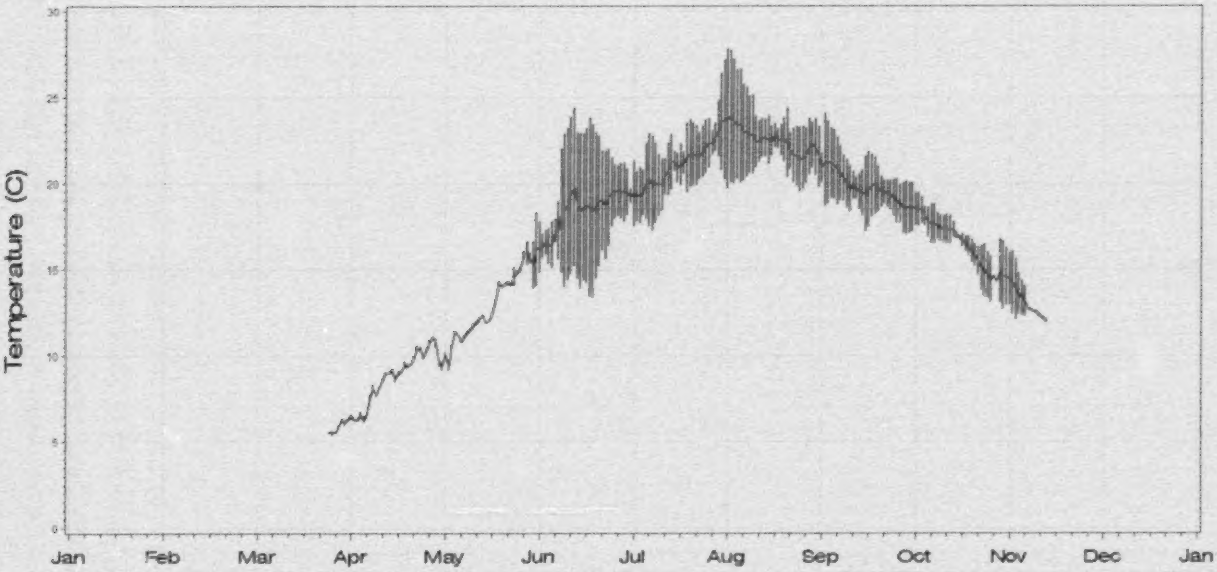
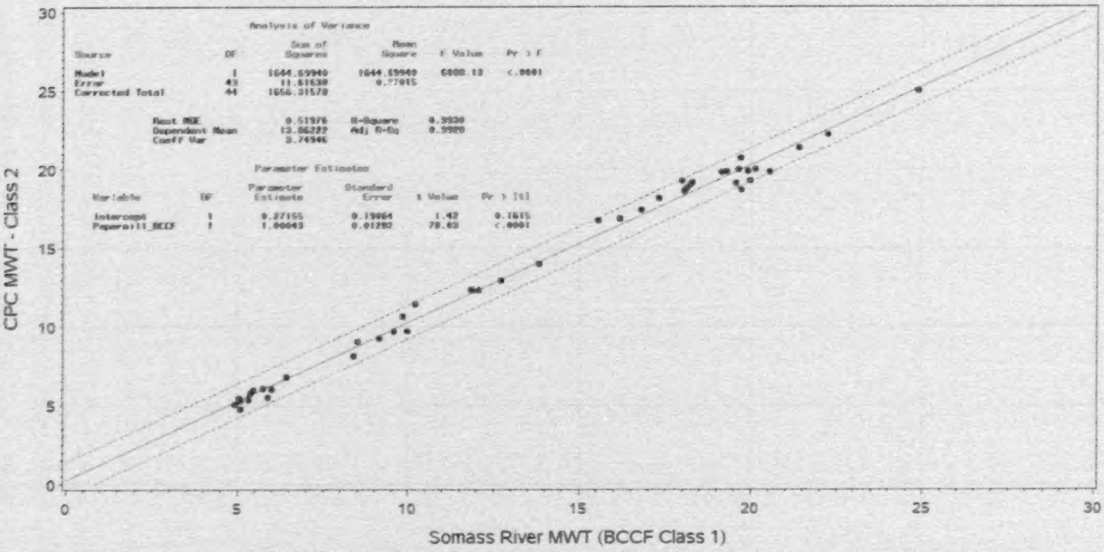


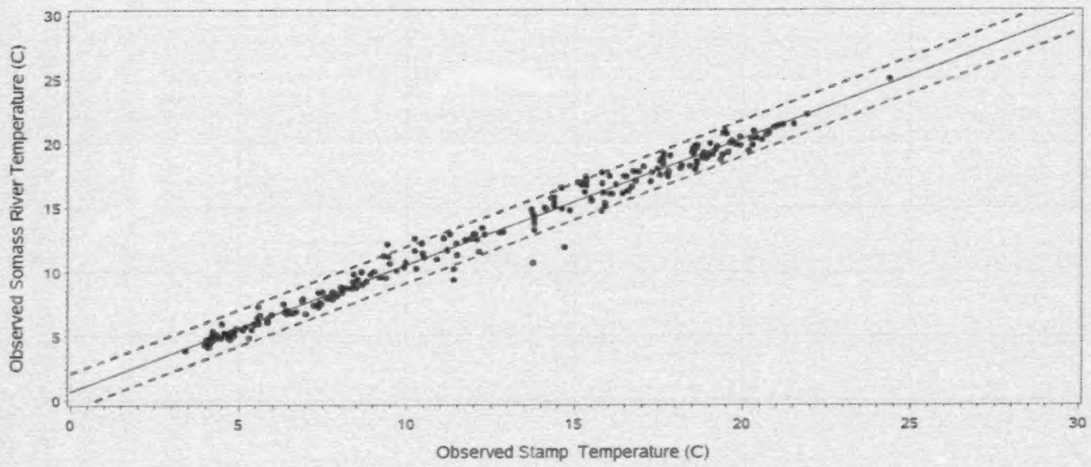
Figure 37. Annual thermograph of mean daily water temperature data ± two standard deviations for Sproat River watershed reference site at Sproat Falls Fishway, 1996, 2000-2003 (Source: DFO SALMON IN REGIONAL ECOSYSTEMS and DFO SOUTH COAST), 2009-2010 (Source: BC CONSERVATION FOUNDATION).



```
                     Analysis of Variance

                             Sum of          Mean
Source             DF       Squares        Square    F Value    Pr > F

Model               1    1644.69940    1644.69940    6088.18    <.0001
Error              43      11.61630       0.27015
Corrected Total    44    1656.31570

        Root MSE              0.51976    R-Square     0.9930
        Dependent Mean       13.86222    Adj R-Sq     0.9928
        Coeff Var             3.74946

                     Parameter Estimates

                        Parameter       Standard
Variable        DF       Estimate          Error    t Value    Pr > |t|

Intercept        1        0.27155        0.19084       1.42      0.1615
Papermill_BCCF   1        1.00043        0.01282      78.03      <.0001
```

30
25
20
15
10
5
0
CPC MWT - Class 2
0
5
10
15
20
25
30
Somass River MWT (BCCF Class 1)

Figure 38. Regression of weekly Class 2 spot temperatures (source: CATALYST PAPER MILL EEM PROGRAM) as a function of daily mean water temperture from Class 1 data logger readings (source: BCCF).



```
                              Analysis of Variance

                                     Sum of           Mean
Source                    DF        Squares         Square    F Value    Pr > F

Model                      1     6515.71057     6515.71057    12944.2    <.0001
Error                    219      110.23788        0.50337
  Lack of Fit            196      104.27644        0.53202       2.05    0.0222
  Pure Error              23        5.96144        0.25919
Corrected Total          220     6625.94845


             Root MSE              0.70949    R-Square     0.9834
             Dependent Mean       12.92916    Adj R-Sq     0.9833
             Coeff Var             5.48748


                              Parameter Estimates

                                   Parameter       Standard
Variable      Label          DF     Estimate          Error    t Value    Pr > |t|

Intercept     Intercept       1      0.68398        0.11774       5.81      <.0001
StampMWT      Daily MWT       1      0.98348        0.00864     113.77      <.0001
```

Figure 39. Relationship between observed Stamp River and Somass River daily mean water temperatures for available data, 2000-2012.

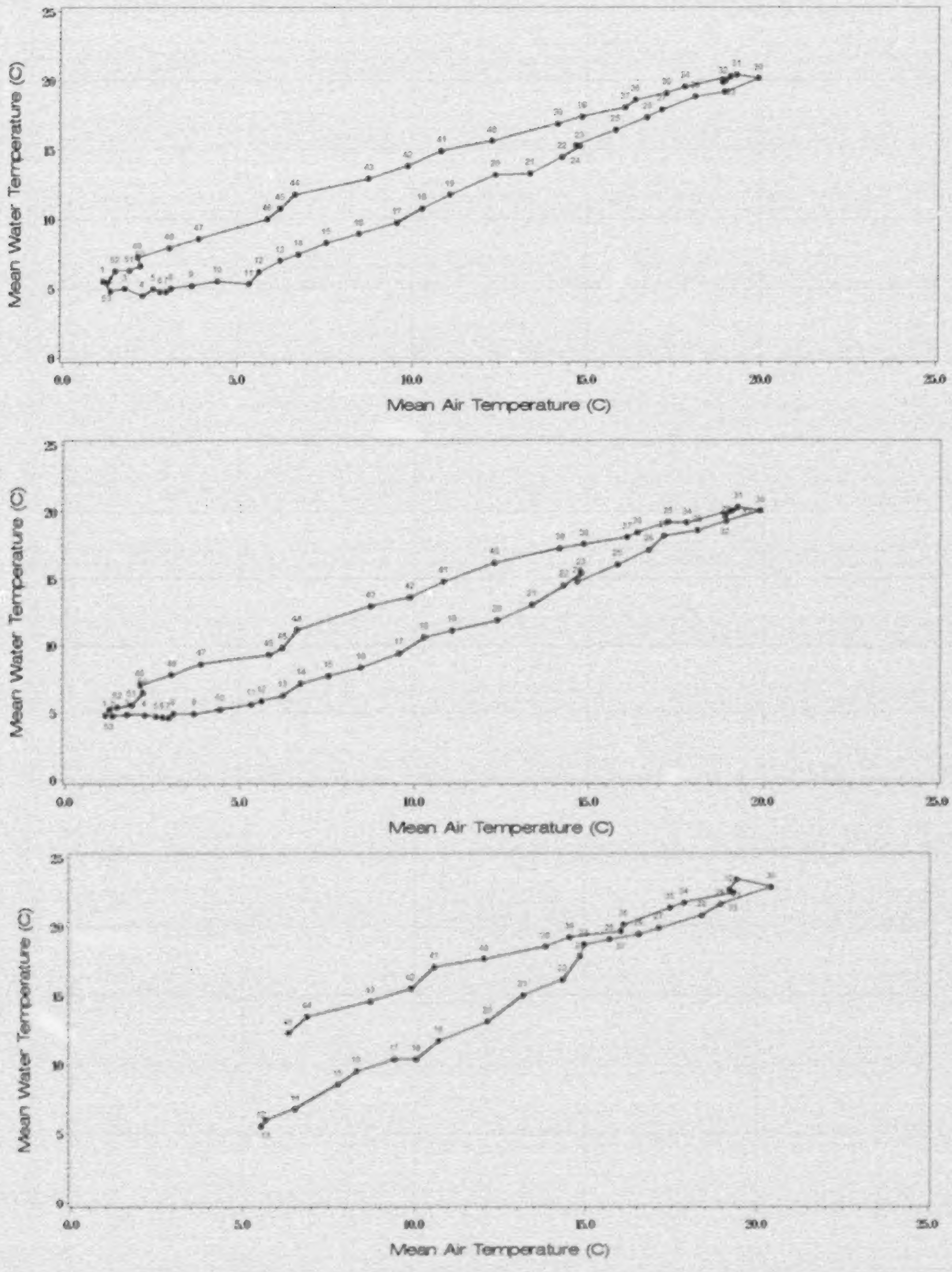


Figure 40. Derivation of seasonal turn-around point for Somass (top), Stamp (middle), and Sproat (bottom) rivers, based on maximum weekly mean air and water temperature data. The seasonal turn-around point for all reference sites is in week 30 or day 210, approx. July 29th. The "warming season" therefore extends from April 1 to July 29th, followed by the "cooling season" from day 211-329, i.e., July 30th – November 25th.

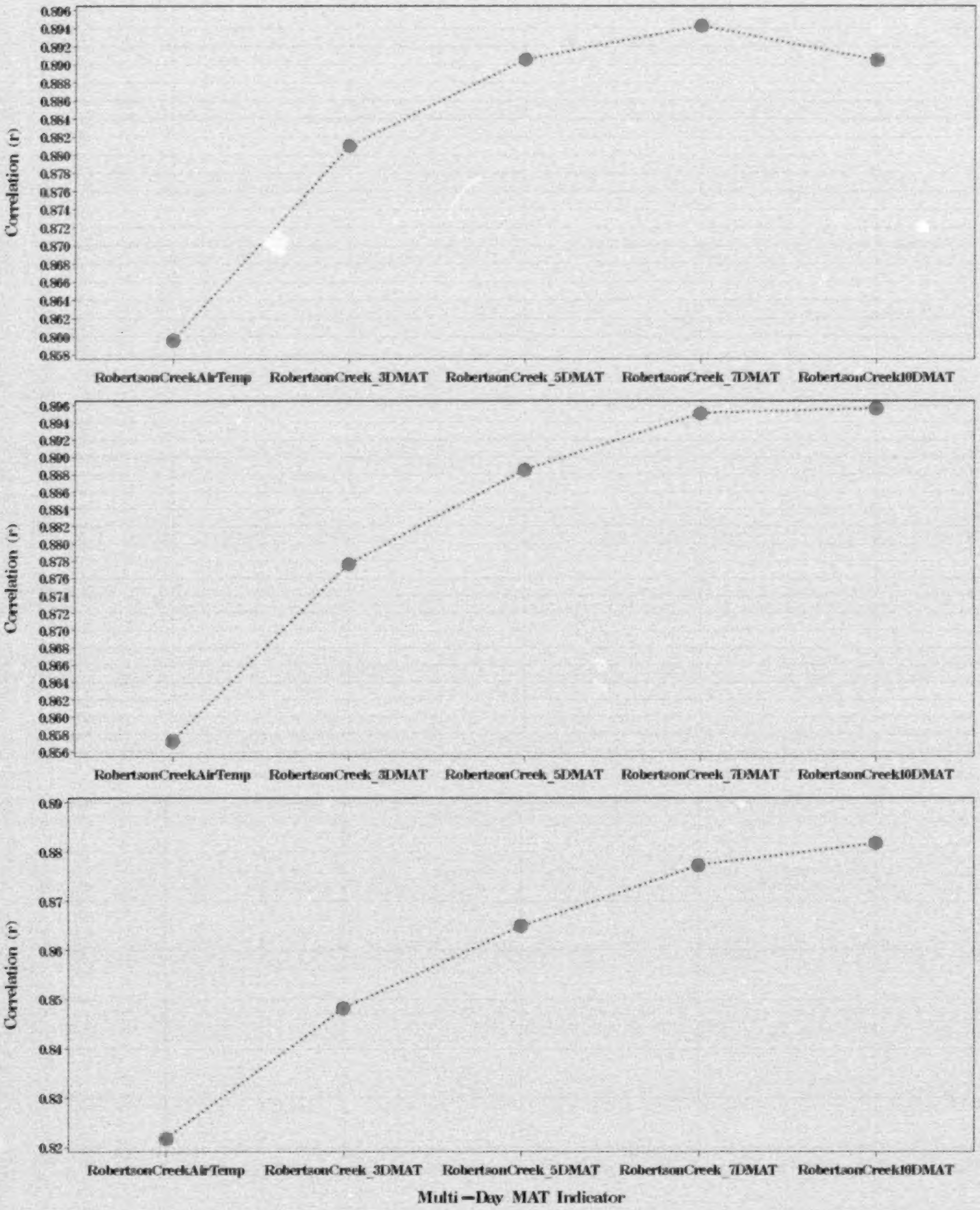
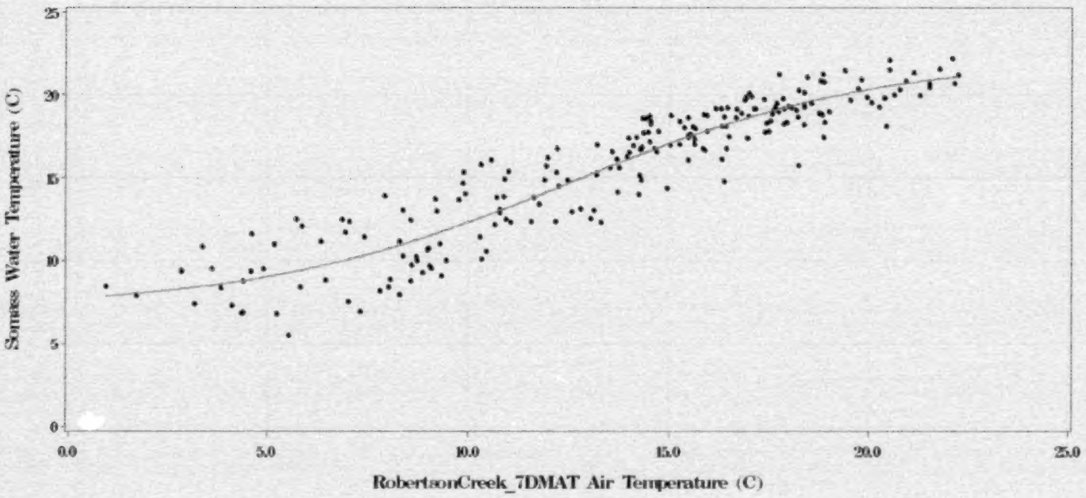


Figure 41. Derivation of optimum regional air temperature index for air/water temperature analyses, based on maximum all-year correlation between various multi-day mean air temperature indicators (MATs) with daily mean water temperature (MWT) in the Somass (top), Stamp (middle), and Sproat (bottom) rivers. Air temperature indicators include (l-r): Robertson Creek Air Temp (same day mean); 3-day centered moving average air temperature (3D-MAT), 5D-MAT, 7D-MAT, and 10-DMAT.



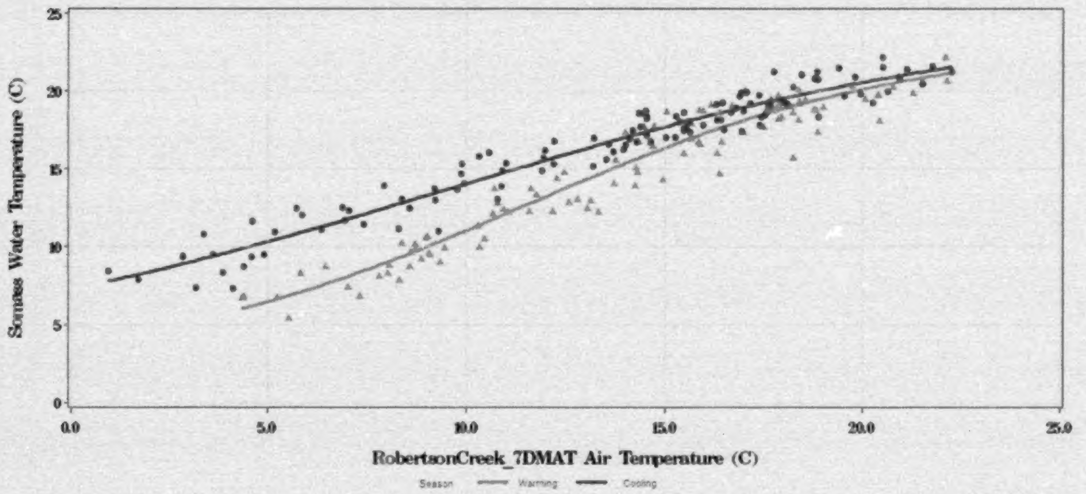


Figure 42. Logistic regression fits for air/water temperature relationship for Somass River daily spot water temperatures as a function of the ROBERTSON CREEK STANDARD 7d-CMAT (air temperature index): seasons combined (top); separate warming season (red) and cooling seasons (blue) (bottom).

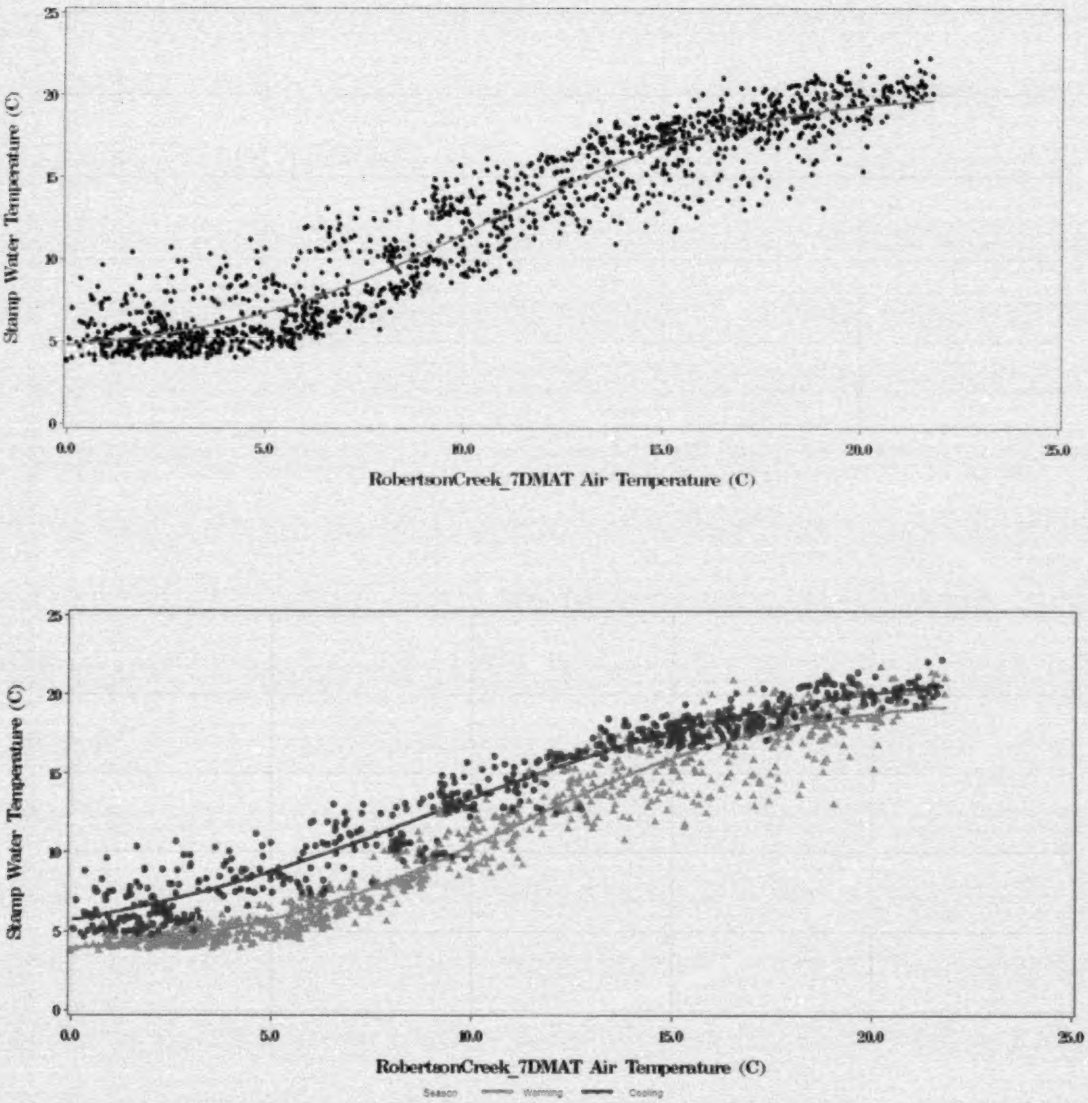


Figure 43. Logistic regression fits for air/water temperature relationship for Stamp River daily mean water temperatures as a function of the ROBERTSON CREEK STANDARD 7d-CMAT (air temperature index): seasons combined (top); separate warming season (red) and cooling seasons (blue) (bottom).

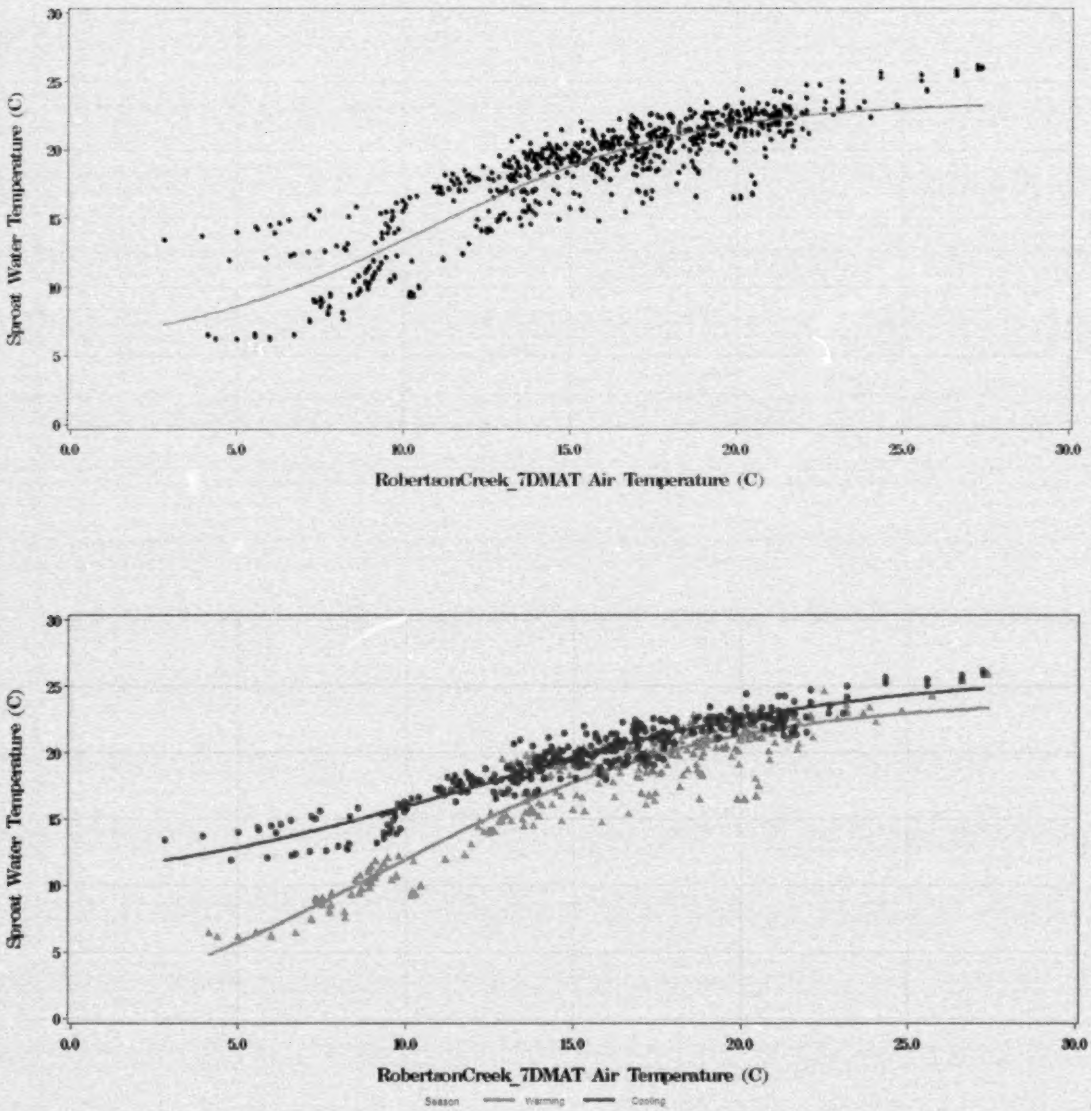


Figure 44. Logistic regression fits for air/water temperature relationship for Sproat River daily mean water temperatures as a function of the ROBERTSON CREEK STANDARD 7d-CMAT (air temperature index): seasons combined (top); separate warming season (red) and cooling seasons (blue) (bottom).

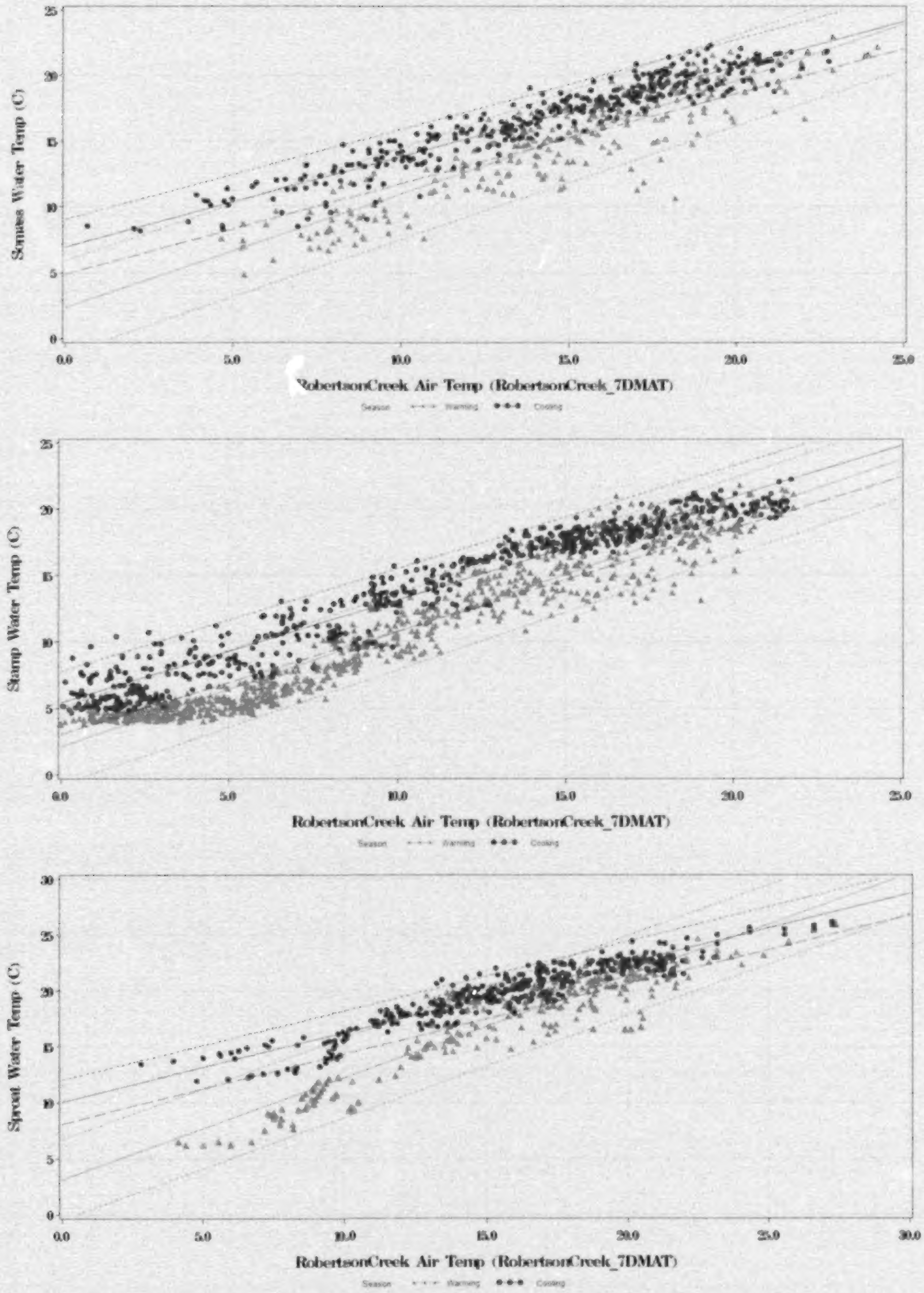


Figure 45. Linear regression fits for air/water temperature relationship for Somass River daily spot water temperatures (top), and Stamp River (middle) and Sproat River (bottom) daily mean water temperatures as a function of the ROBERTSON CREEK STANDARD 7d-CMAT (air temperature index), by season (warming season (red) and cooling season (blue)).

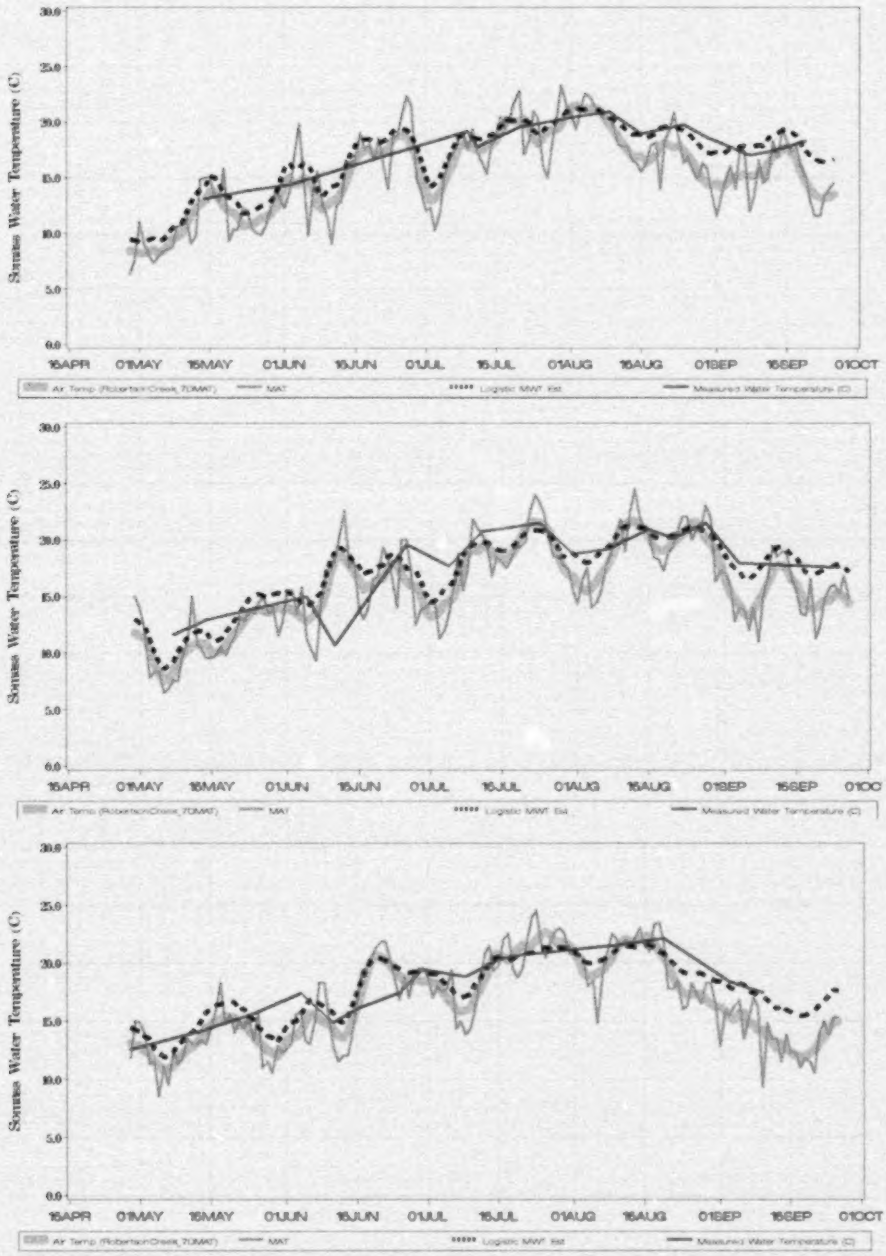


Figure 46. Sample validation plots of daily mean air temperature (red line), 7-day MAT index (broad pink line), and observed (blue solid line) and estimated (black dashed line, based on seasonal logistic regression models) daily mean water temperature for Somass River, May-Oct 2000 (top), 2002 (middle), 2004 (bottom).

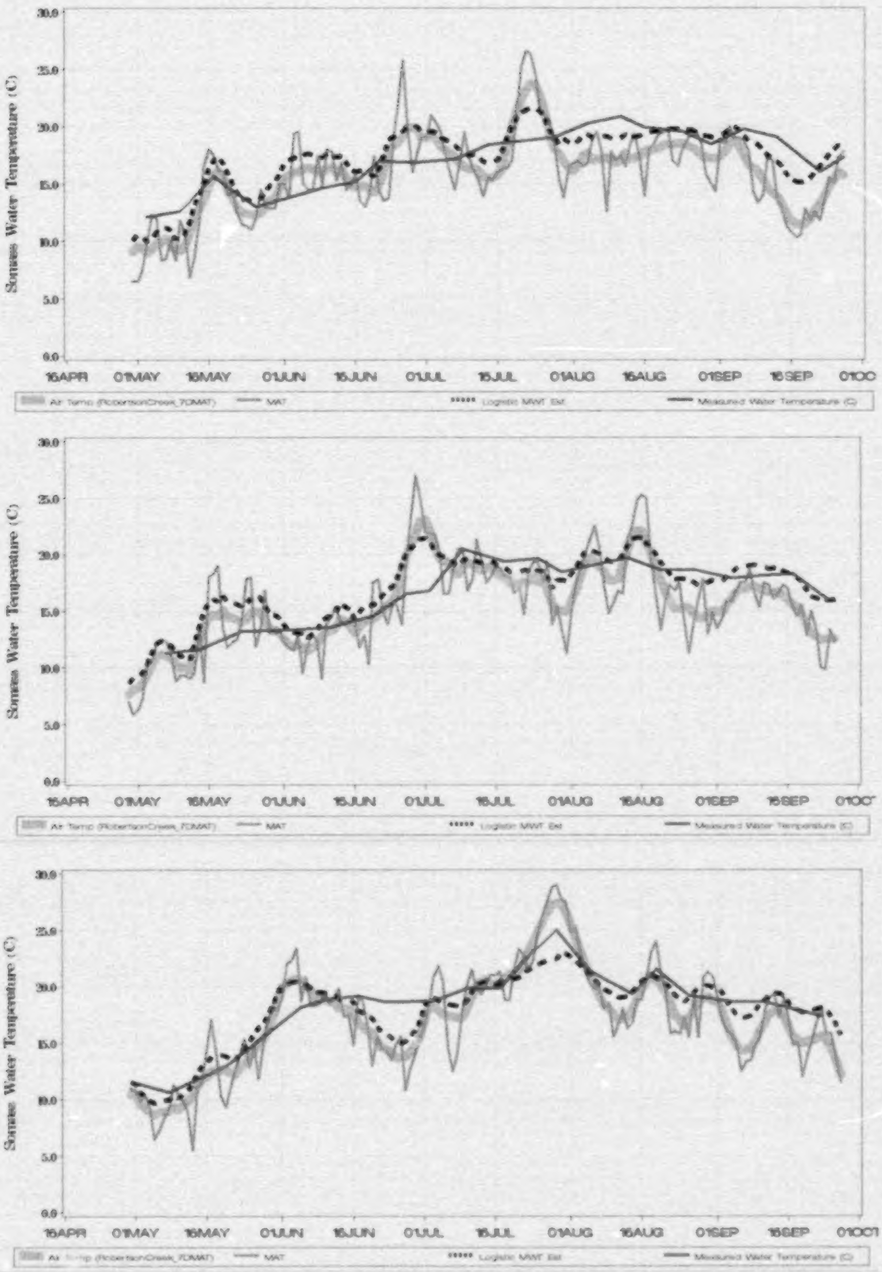


Figure 47. Sample validation plots of daily mean air temperature (red line), 7-day MAT index (broad pink line), and observed (blue solid line) and estimated (black dashed line, based on seasonal logistic regression models) daily mean water temperature for Somass River, May-Oct 2006 (top), 2008 (middle), 2009 (bottom).

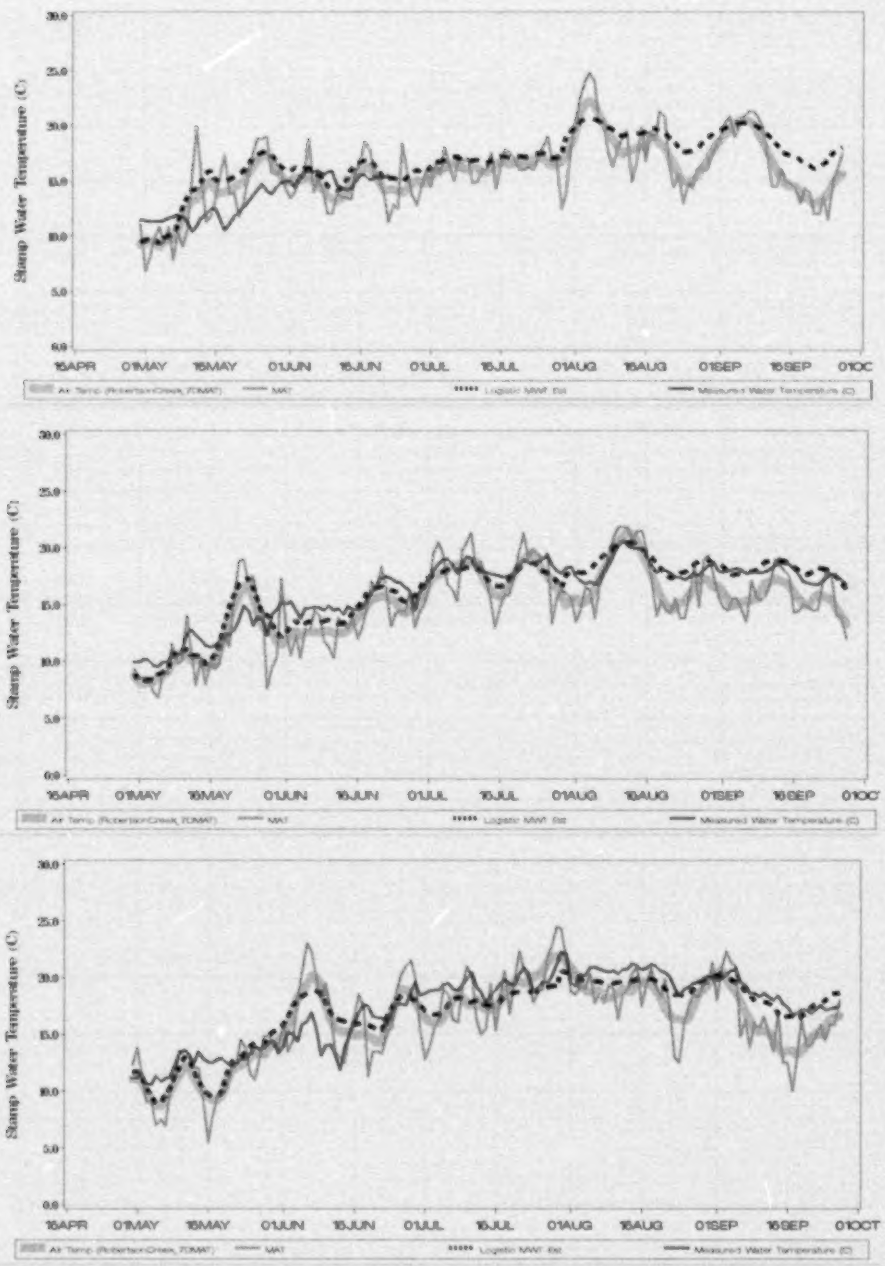


Figure 48. Sample validation plots of daily mean air temperature (red line), 7-day MAT index (broad pink line), and observed (blue solid line) and estimated (black dashed line, based on seasonal logistic regression models) daily mean water temperature for Stamp River, May-Oct 1993 (top), 2001 (middle), 2003 (bottom).

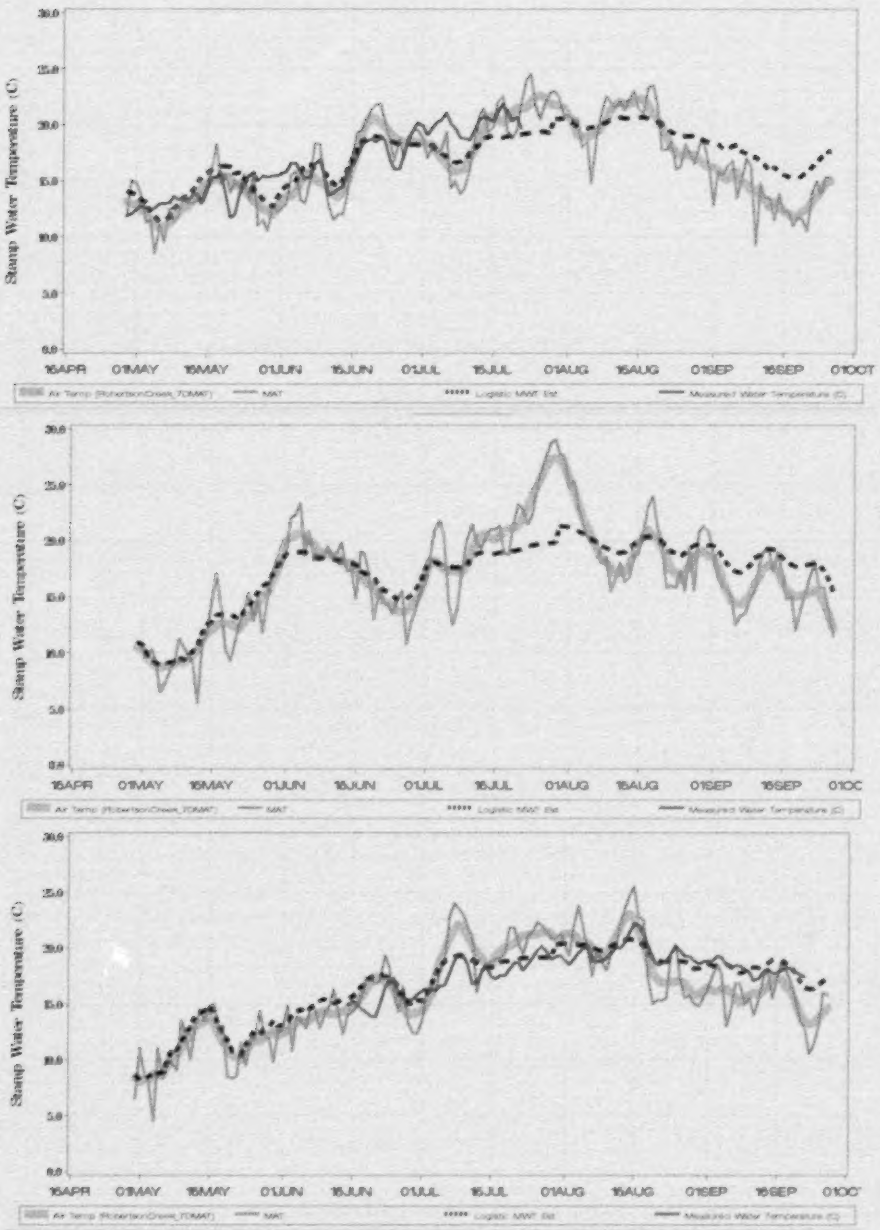


Figure 49. Sample validation plots of daily mean air temperature (red line), 7-day MAT index (broad pink line), and observed (blue solid line) and estimated (black dashed line, based on seasonal logistic regression models) daily mean water temperature for Stamp River, May-Oct 2004 (top), 2009 (middle), 2010 (bottom).

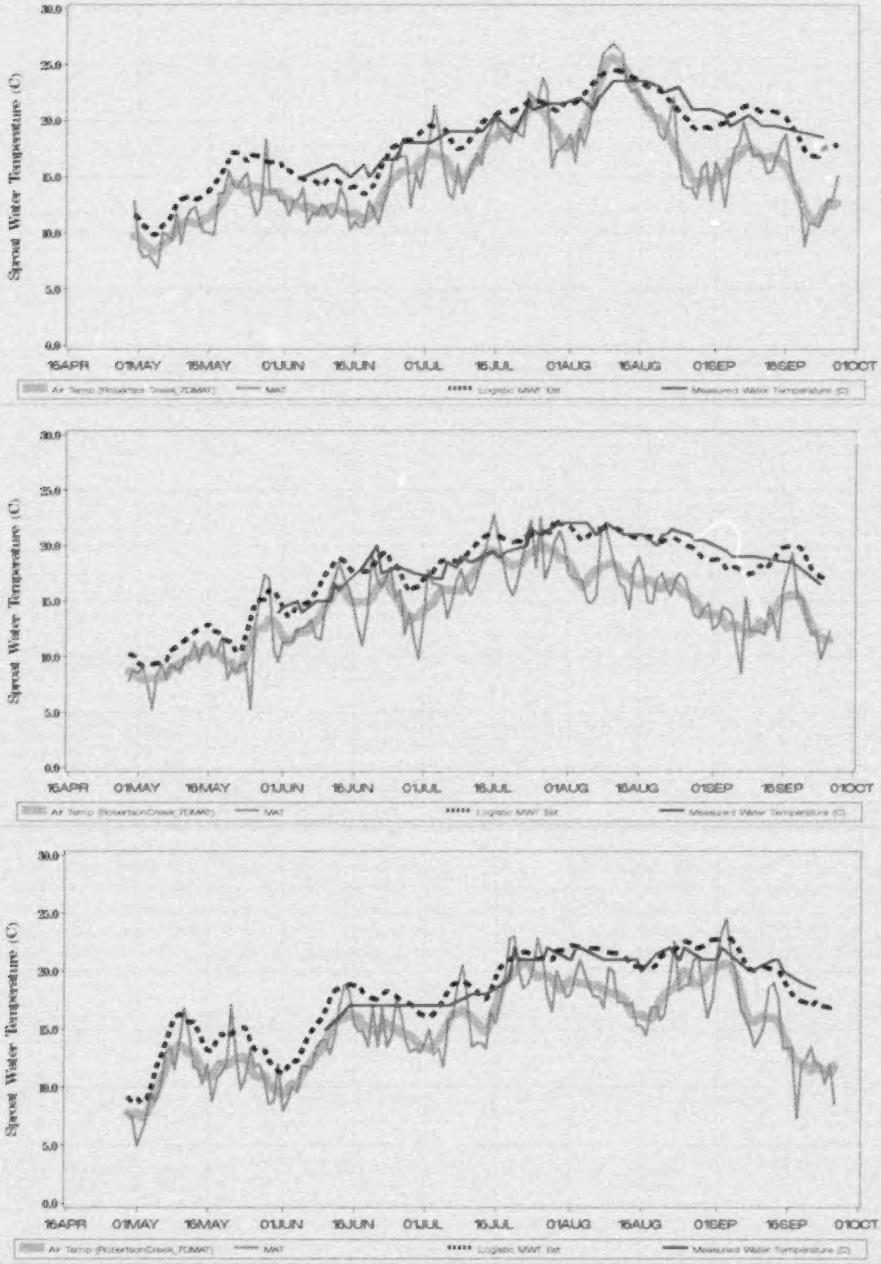


Figure 50. Sample validation plots of daily mean air temperature (red line), 7-day MAT index (broad pink line), and observed (blue solid line) and estimated (black dashed line, based on seasonal logistic regression models) daily mean water temperature for Sproat River, May-Oct 1981 (top), 1984 (middle), 1988 (bottom).

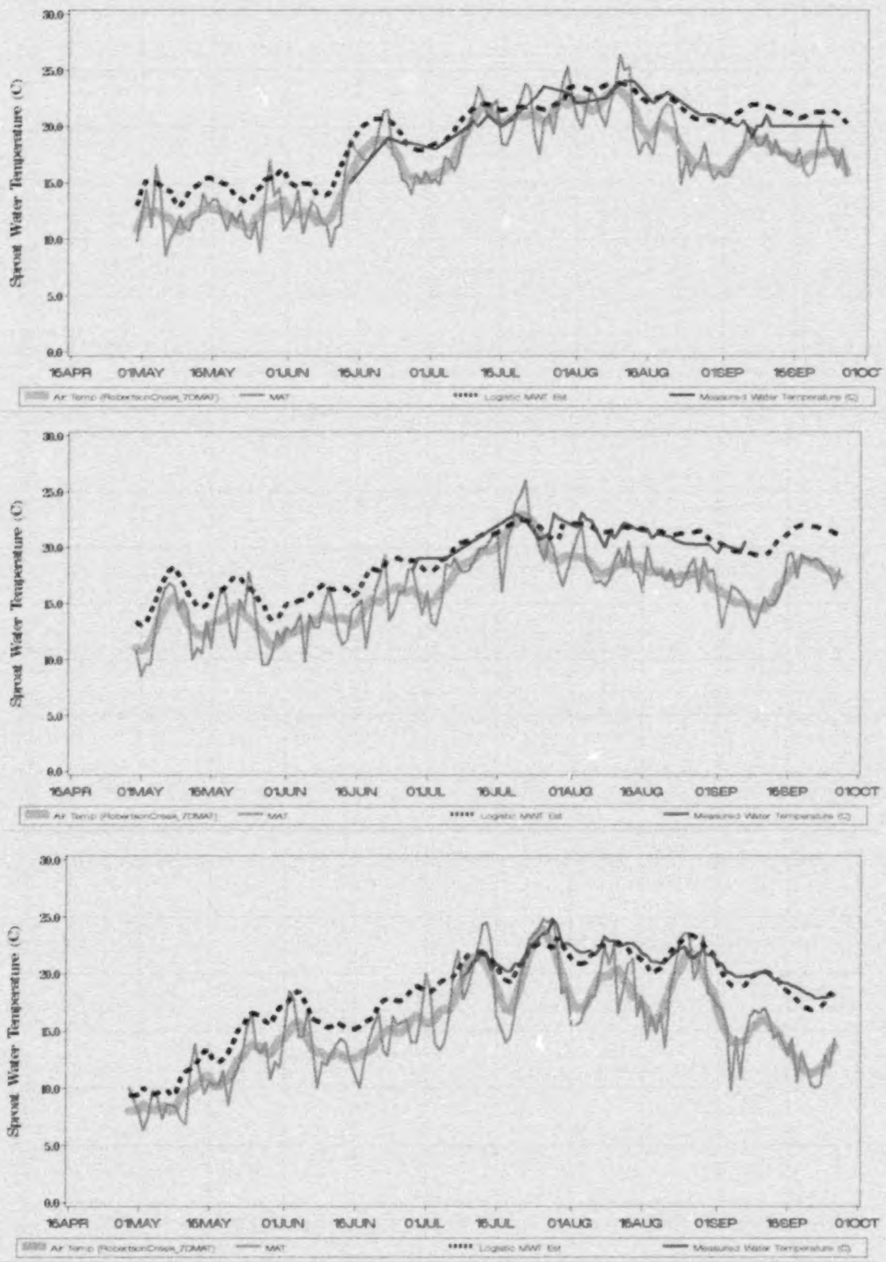


Figure 51. Sample validation plots of daily mean air temperature (red line), 7-day MAT index (broad pink line), and observed (blue solid line) and estimated (black dashed line, based on seasonal logistic regression models) daily mean water temperature for Sproat River, May-Oct 1990 (top), 1994 (middle), 1996 (bottom).

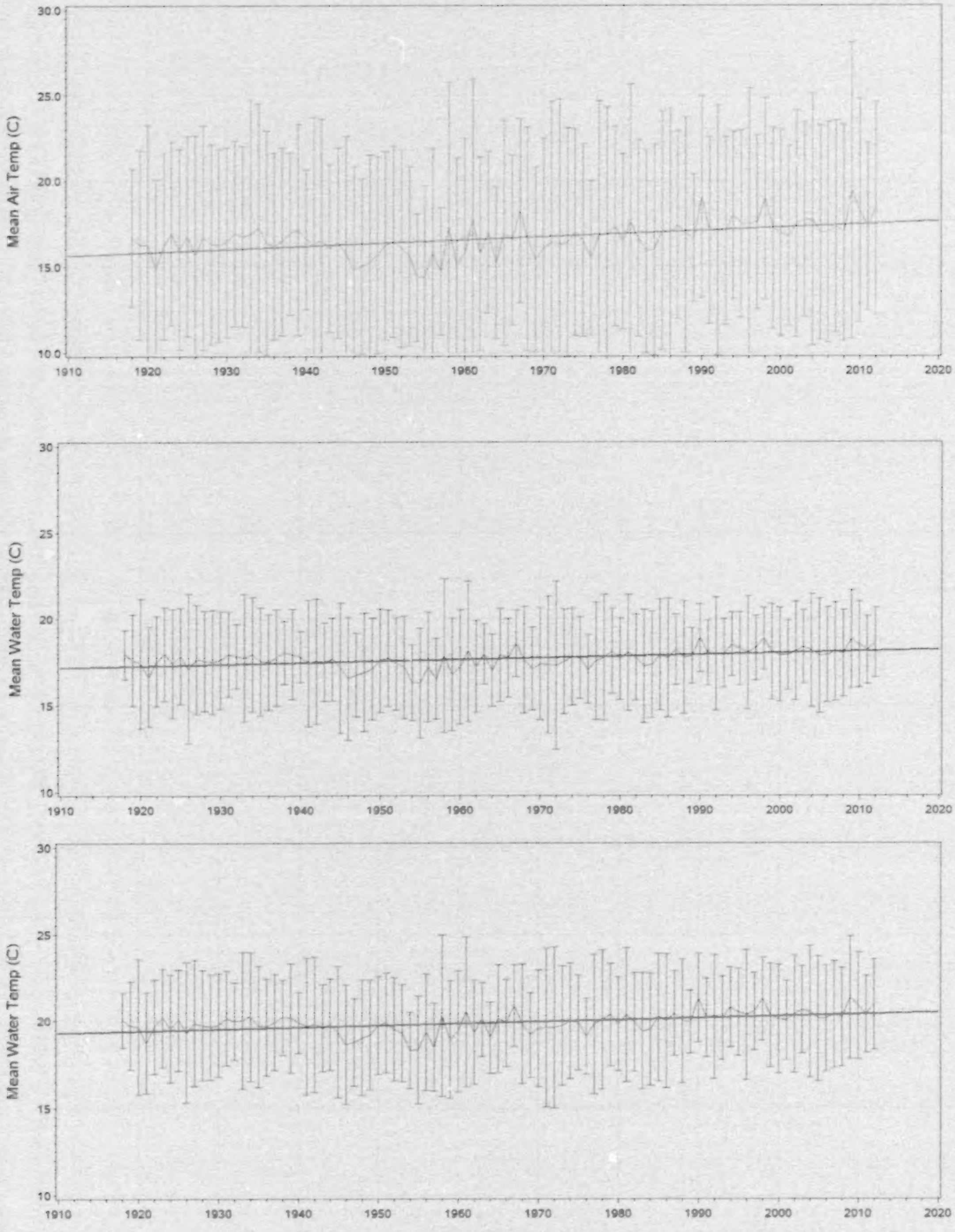


Figure 52. Trends in summer (Jul-Sep) temperature indices. Robertson Creek mean air temperature (top), modeled Stamp water temperature (middle), and modeled Sproat River water temperature (bottom).

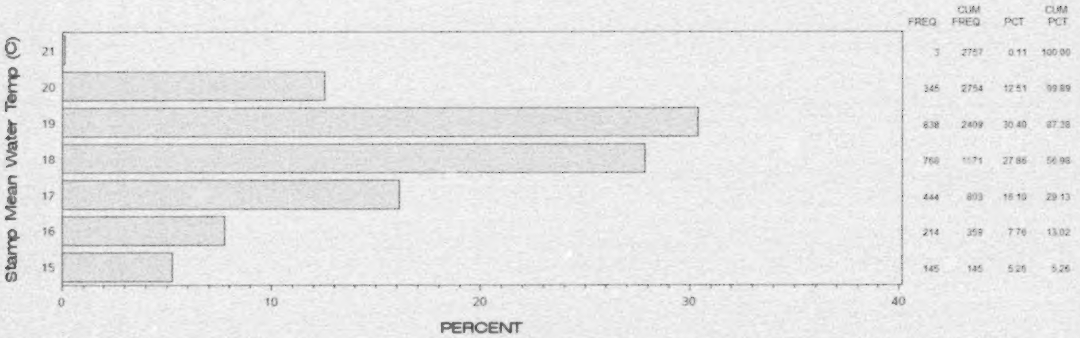


Figure 53. Frequency plot of historical GCL sockeye migration (unweighted tally of non-zero migration dates), at varying levels of Stamp River water temperature. 58% of migration dates occur at 18-19°C.

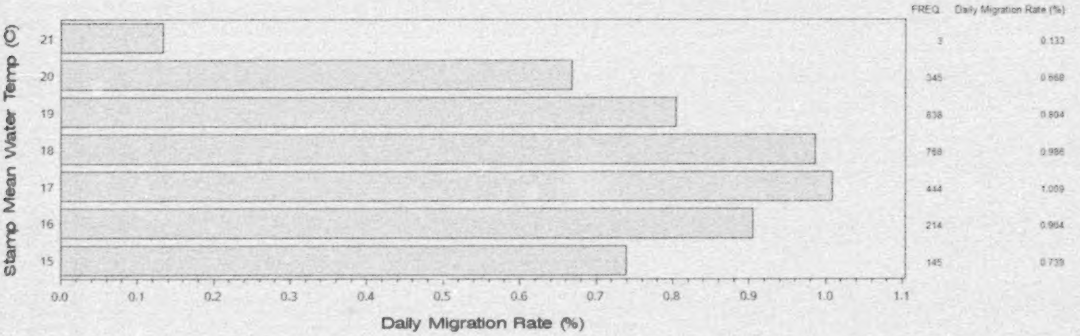
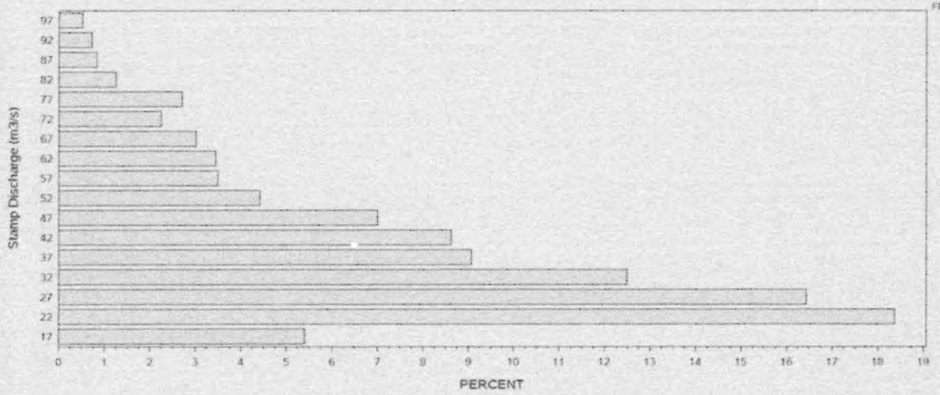
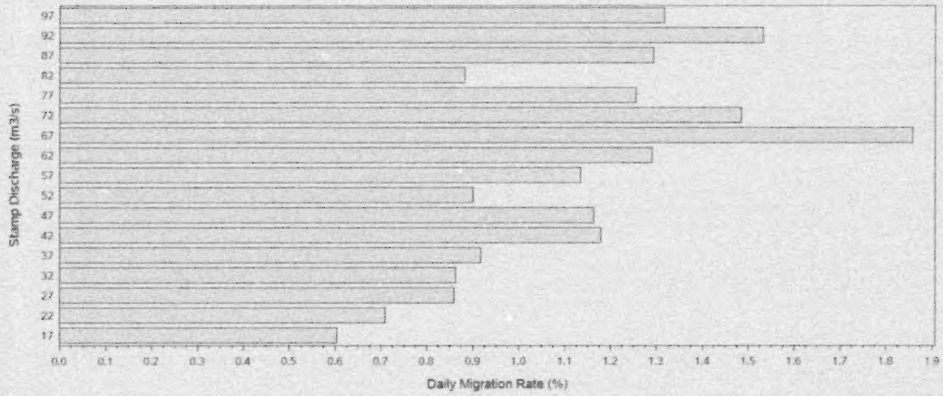


Figure 54. Frequency plot of historical GCL sockeye non-zero migration dates (weighted by daily migration rate), at varying levels of Stamp River water temperature. Though most dates of migration occur at 18-19°C (Figure 53), the highest rates of daily migration occur at 16-18°C.



FREQ	CUM FREQ	PCT	CUM PCT
18	3516	0.51	100.00
25	3498	0.71	99.49
29	3473	0.82	98.78
44	3444	1.25	97.96
95	3400	2.70	96.70
79	3305	2.25	94.00
106	3226	3.01	91.75
121	3120	3.44	88.74
123	2999	3.50	85.30
155	2876	4.41	81.80
246	2721	7.00	77.39
303	2475	8.62	70.39
319	2172	9.07	61.77
439	1853	12.49	52.70
578	1414	16.44	40.22
646	836	18.37	23.78
190	190	5.40	5.40

Figure 55. Frequency plot of historical GCL sockeye migration (unweighted tally of non-zero migration dates), at varying levels of Stamp River discharge. Most migration dates (~70%) occur at 20-50 cms.



FREQ	Daily Migration Rate (%)
18	1.32
25	1.53
29	1.29
44	0.88
95	1.26
79	1.48
106	1.86
121	1.29
123	1.13
155	0.90
246	1.16
303	1.18
319	0.92
439	0.86
578	0.86
646	0.71
190	0.60

Figure 56. Frequency plot of historical GCL sockeye non-zero migration dates (weighted by daily migration rate), at varying levels of Stamp River discharge. Though most dates of migration occur at 20-50 cms (Figure 53), the highest rates of daily migration occur at > 40 cms, with maximum daily migration rates between 60-90 cms.

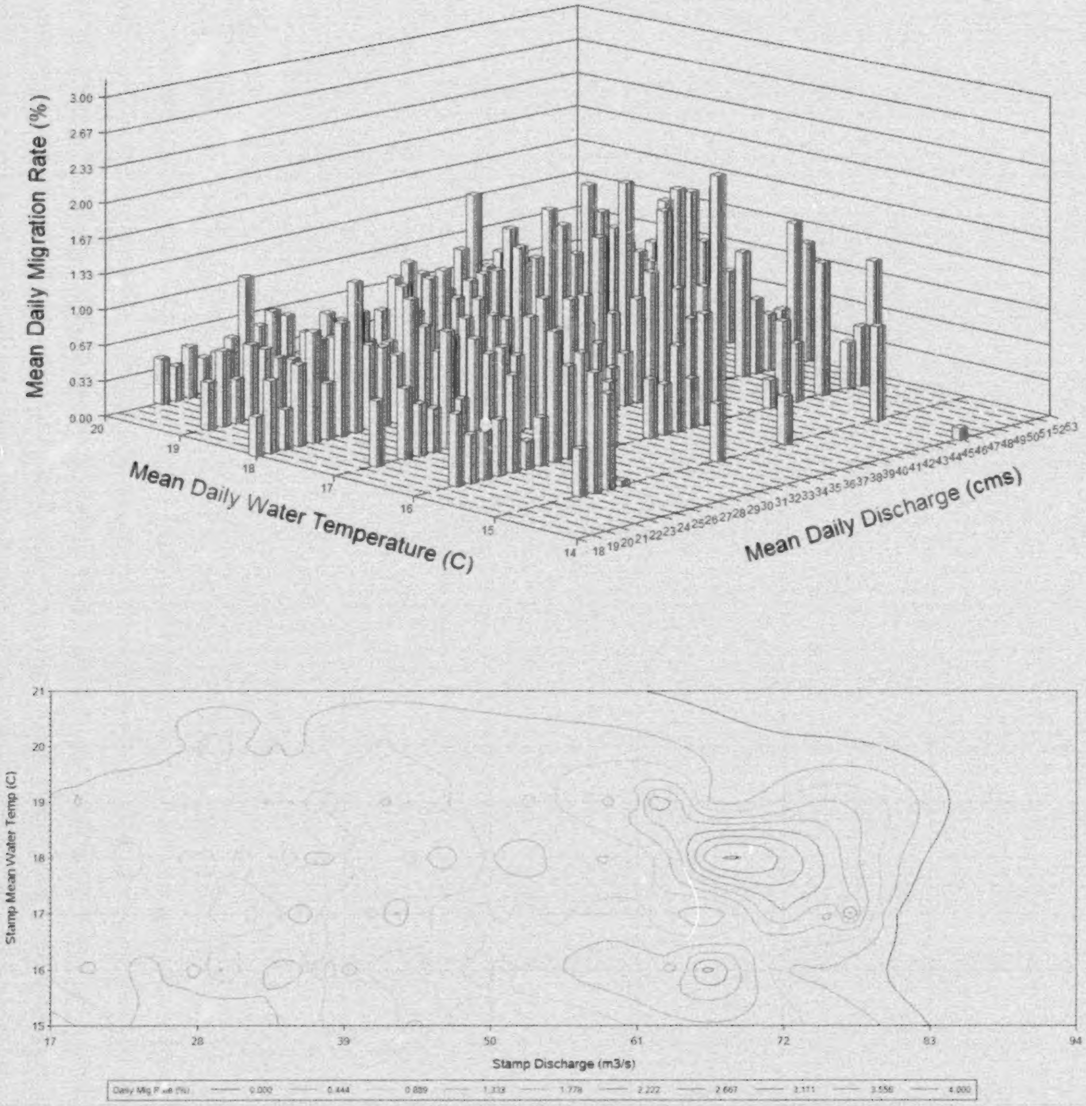
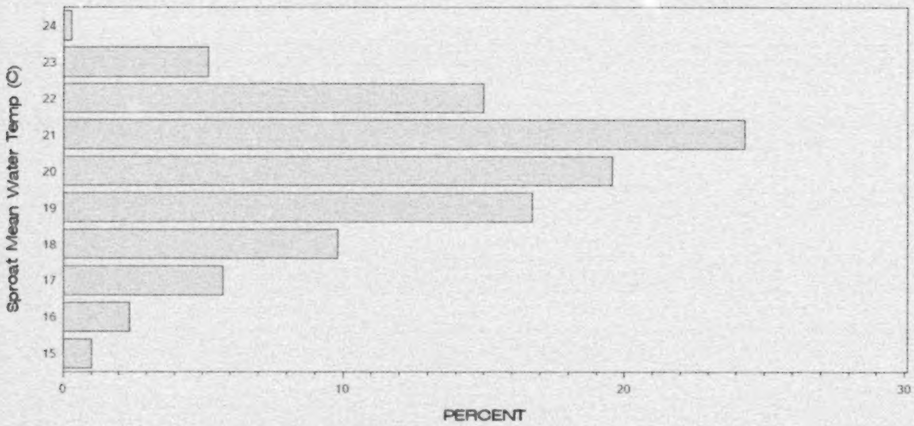
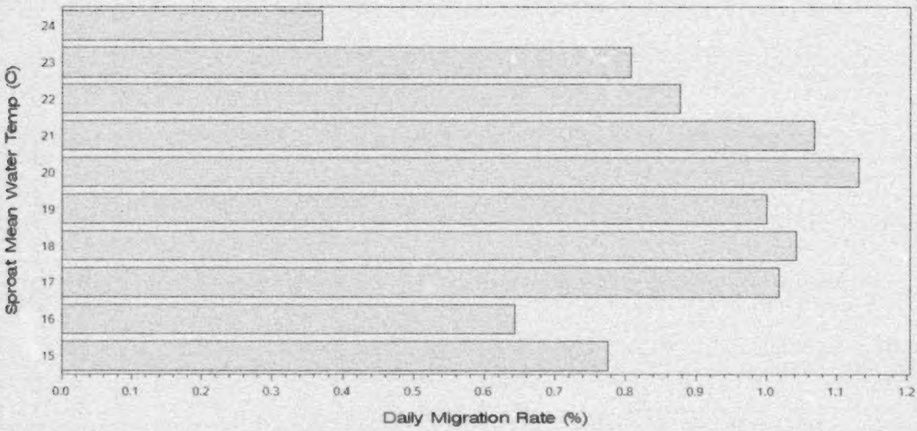


Figure 57. Weighted frequency plot (top) and smoothed contour (bottom) of historical Great Central Lake sockeye (1976-2012) mean daily migration rates (%), at varying levels of Stamp River water temperature and discharge. Filtered for a minimum of 5 observations at each MWT x Flow point. Maximum migration rates are found at 16-18°C and 60-70 cms.



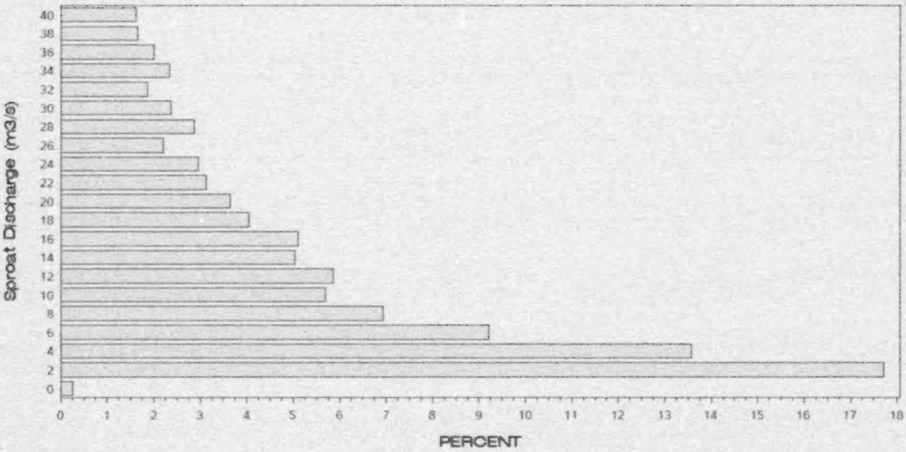
FREQ	CUM FREQ	PCT	CUM PCT
10	3591	0.28	100.00
187	3581	5.21	99.72
538	3394	14.98	94.51
872	2856	24.28	79.53
703	1984	19.58	55.25
600	1281	16.71	35.67
353	681	9.83	18.96
206	328	5.74	9.13
86	122	2.39	3.40
36	36	1.00	1.00

Figure 58. Frequency plot of historical Sproat sockeye migration dates (unweighted tally of non-zero migration dates), at varying levels of Sproat River water temperature. Most dates (66%) of migration occur at 19-22°C.



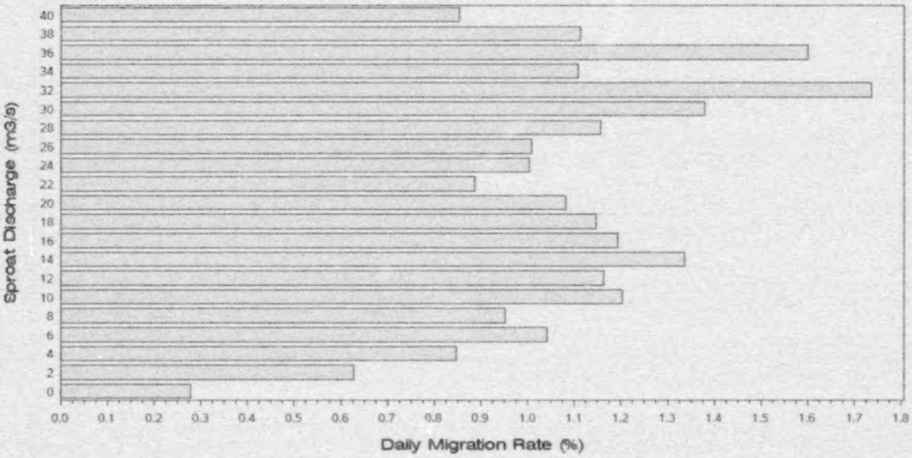
FREQ	Daily Migration Rate (%)
10	0.370
187	0.807
538	0.877
872	1.068
703	1.131
600	1.000
353	1.042
206	1.018
86	0.643
36	0.775

Figure 59. Frequency plot of historical Sproat sockeye non-zero migration dates (weighted by daily migration rate), at varying levels of Sproat River water temperature. Though most dates of migration occur at 20-21°C (Figure 58), the highest rates of migration occur at 17-21°C.



FREQ	CUM FREQ	PCT.	CUM PCT.
58	3591	1.62	100.00
59	3533	1.64	98.38
72	3474	2.01	96.74
84	3402	2.34	94.74
67	3318	1.87	92.40
85	3251	2.37	90.53
103	3166	2.87	88.16
79	3063	2.20	85.30
106	2984	2.95	83.10
112	2878	3.12	80.14
131	2766	3.65	77.03
145	2635	4.04	73.38
183	2490	5.10	69.34
181	2307	5.04	64.24
210	2126	5.85	59.20
204	1916	5.68	53.36
249	1712	6.93	47.67
331	1463	9.22	40.74
487	1132	13.56	31.52
636	645	17.71	17.96
9	9	0.25	0.25

Figure 60. Frequency plot of historical Sproat sockeye migration (unweighted tally of non-zero migration dates), at varying levels of Sproat River discharge. ~50% of migration dates occur at < 10 cms.



FREQ	Daily Migration Rate (%)
58	0.85
59	1.11
72	1.60
84	1.11
67	1.74
85	1.38
103	1.16
79	1.01
106	1.00
112	0.89
131	1.08
145	1.15
183	1.19
181	1.34
210	1.16
204	1.20
249	0.95
331	1.04
487	0.85
636	0.63
9	0.28

Figure 61. Frequency plot of historical Sproat sockeye non-zero migration dates (weighted by daily migration rate), at varying levels of Sproat River discharge. Though most dates of migration occur at < 10 cms (Figure 60), significant migration rates mostly occur at 10 cms and above, with the highest rates of migration at 30-36 cms.

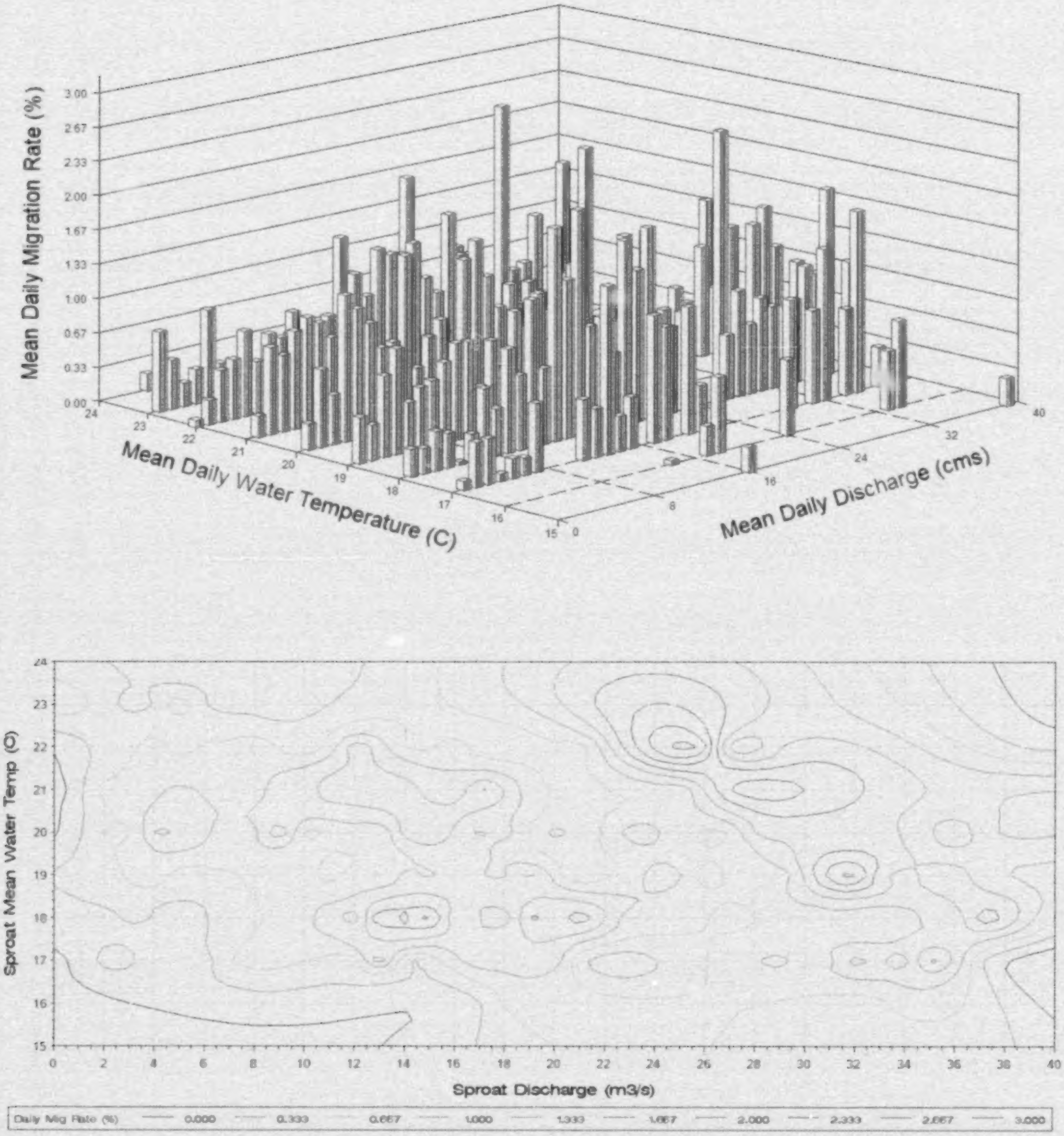


Figure 62. Weighted frequency plot (top) and smoothed contour (bottom) of historical Sproat Lake sockeye (1974-2012) mean daily migration rates (%), at varying levels of Sproat River water temperature and discharge. Filtered for a minimum of 5 observations at each MWT x Flow point. Maximum migration rates are found at 18°C at lower discharges (12-22 cms), and at 19-23°C at discharge rates above 22 cms.

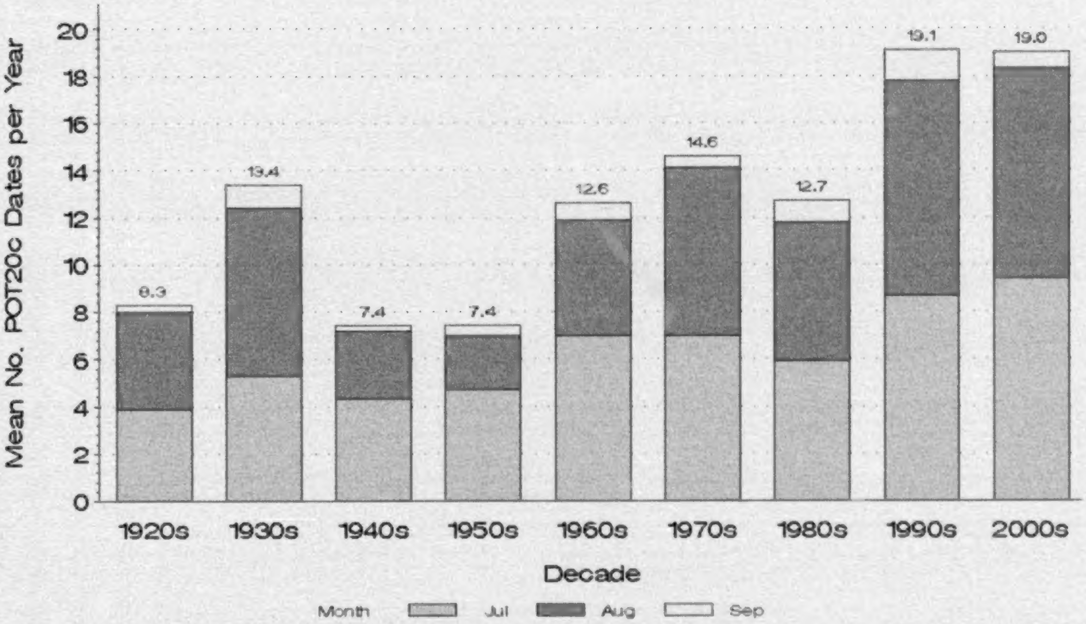


Figure 63. Frequency of decadal mean number of dates per summer month in which mean air temperature (ROBERTSON CREEK STANDARD) exceeded 20°C during sockeye migration, by month.

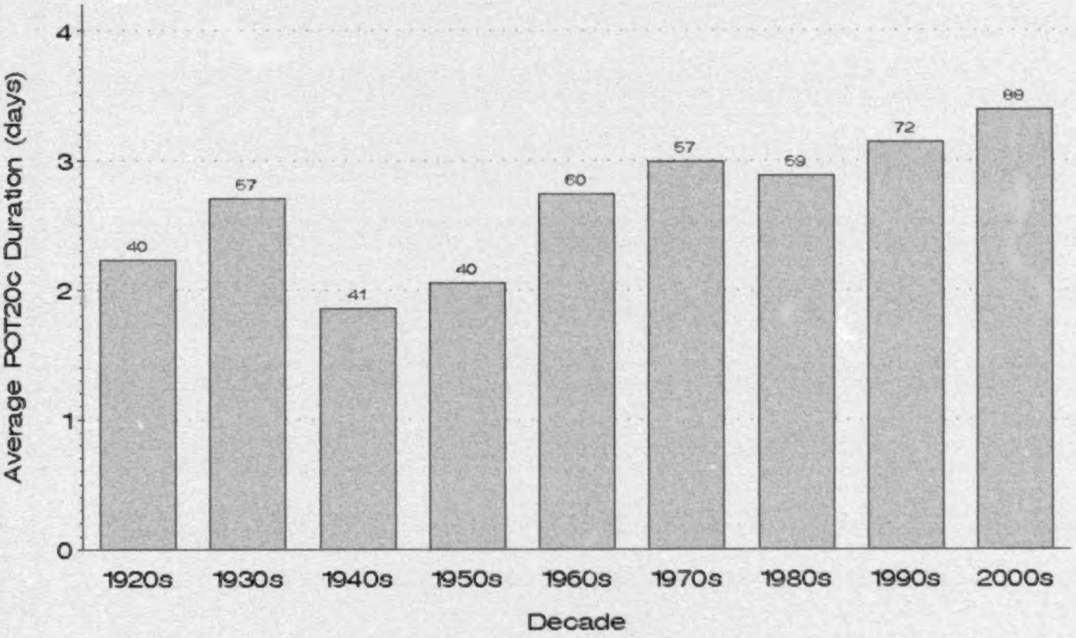


Figure 64. Mean length (days) and total decadal frequency of periods in which mean air temperature (ROBERTSON CREEK STANDARD) continuously exceeded 20°C in Jul-Aug-Sep, by decade.

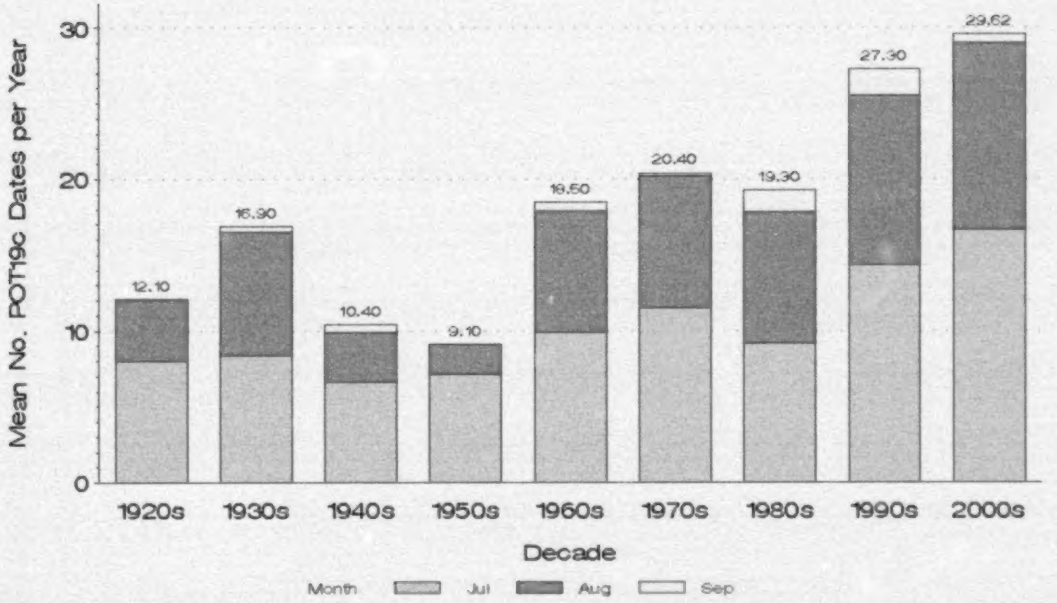


Figure 65. Frequency of decadal mean number of dates per summer month in which mean water temperature (estimated) in the Stamp River exceeded 19°C.

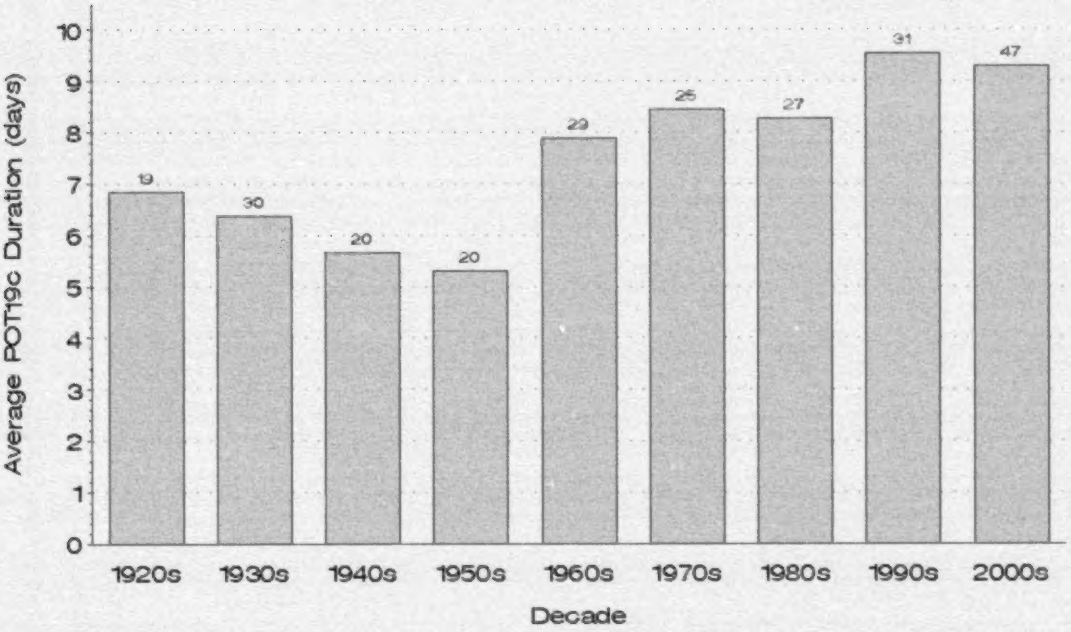


Figure 66. Mean length (days) and total decadal frequency of periods in which mean water temperature (estimated) in the Stamp River continuously exceeded 19°C, by decade.

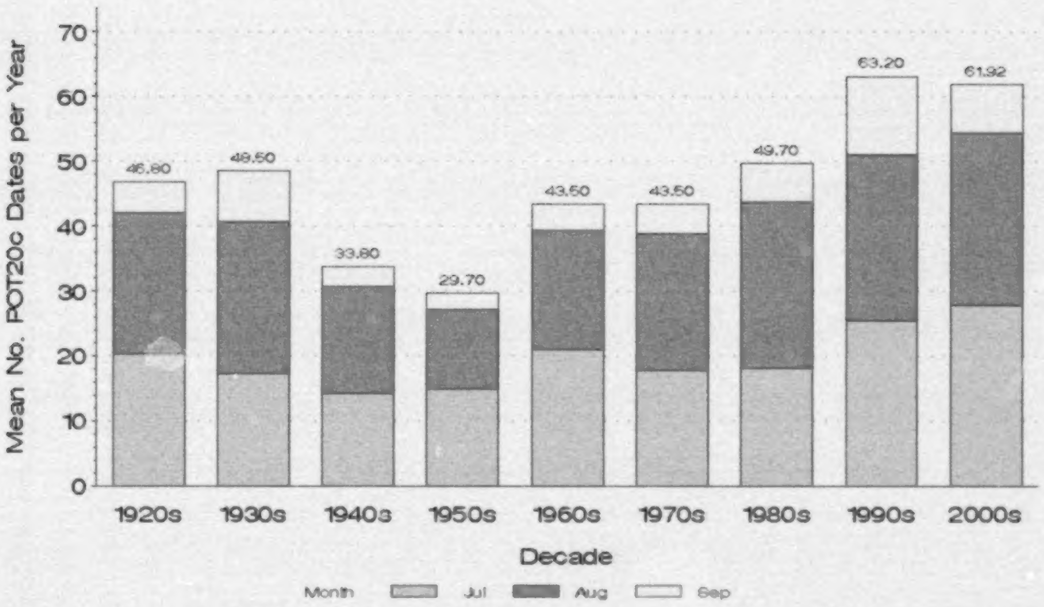


Figure 67. Frequency of decadal mean number of dates per summer month in which mean water temperature (estimated) in the Sproat River exceeded 20°C.

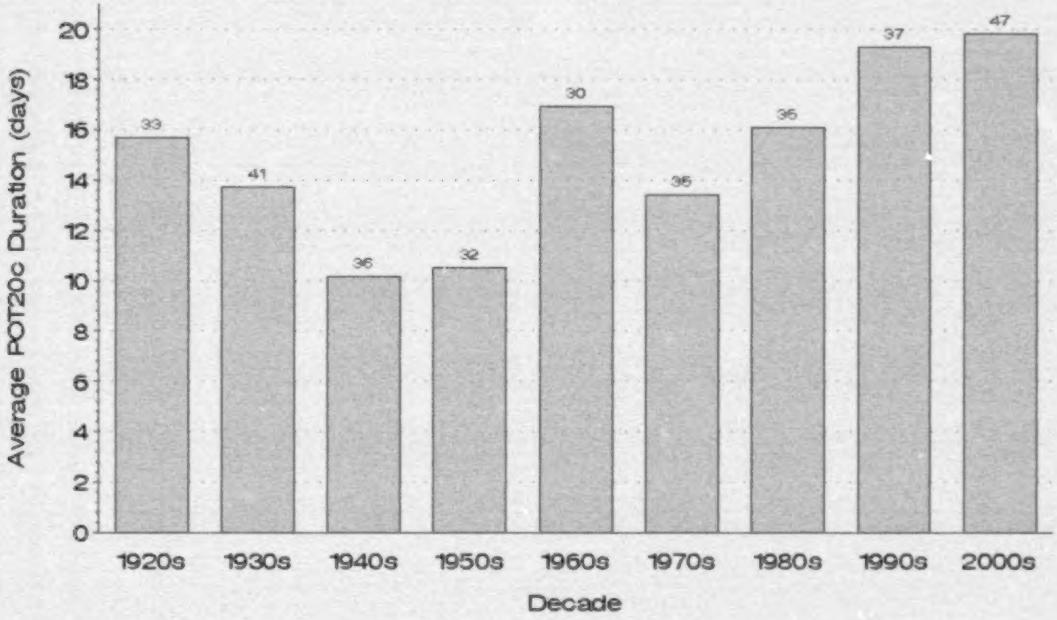


Figure 68. Mean length (days) and decadal total frequency of periods in which mean water temperature (estimated) in the Sproat River continuously exceeded 20°C, by decade.

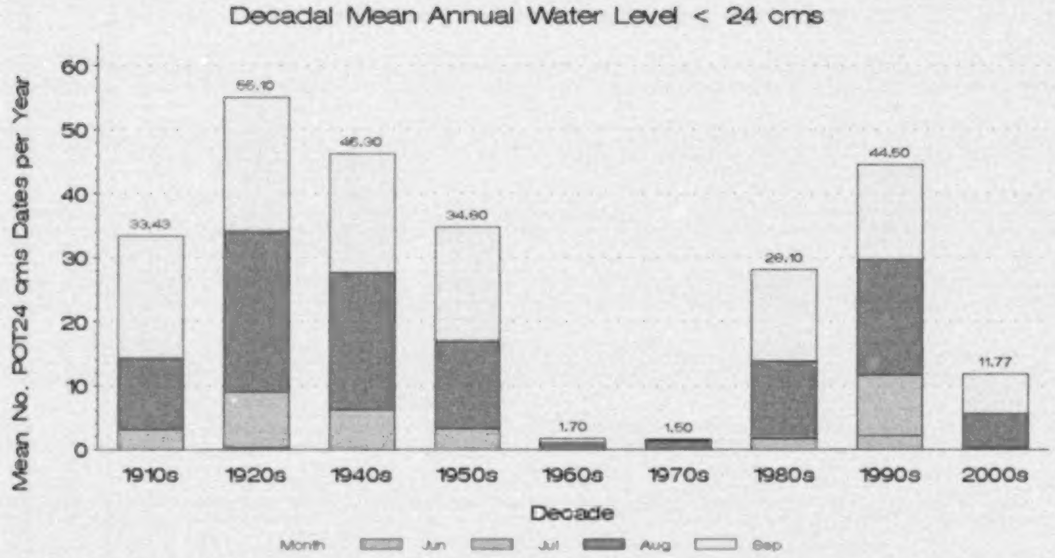


Figure 69. Frequency of decadal mean number of dates per month in which estimated mean daily flow in the Stamp River was less than 24 cms (~25th percentile of historic summer flows).

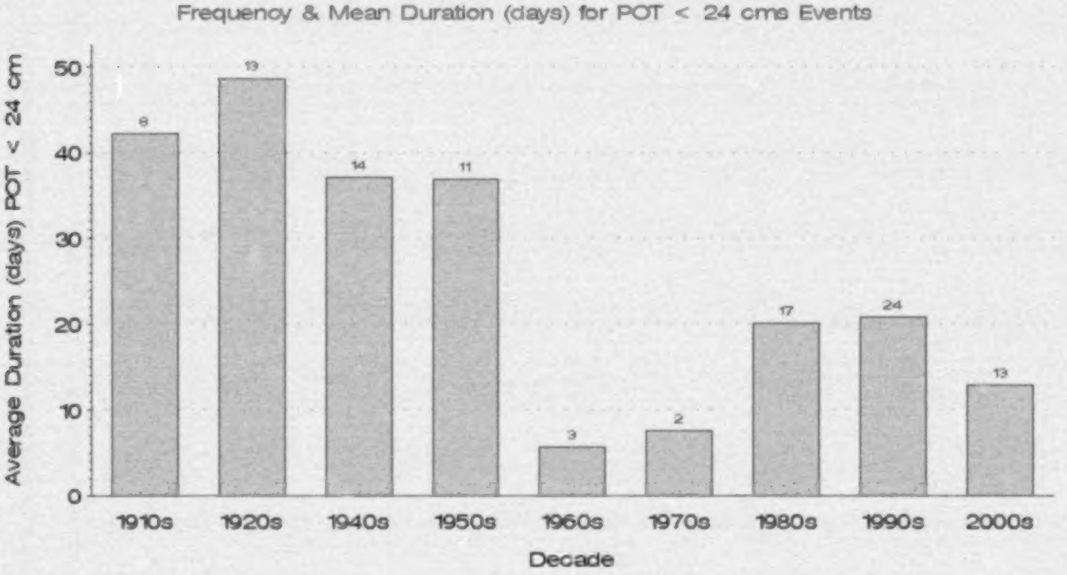


Figure 70. Mean length (days) and mean frequency of number of periods in which estimated mean daily flow in the Stamp River was less than 24 cms, by decade.

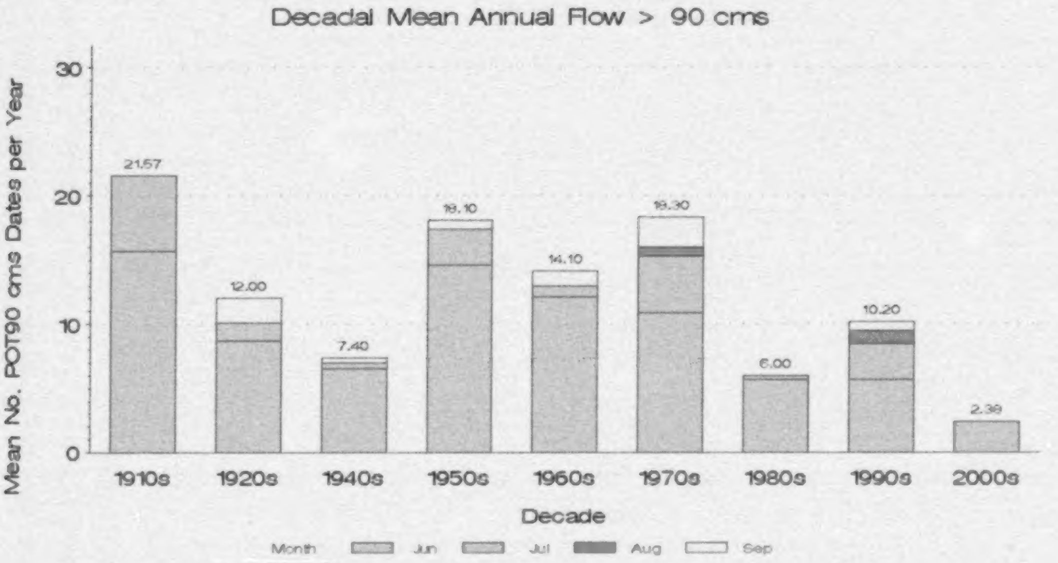


Figure 71. Frequency of decadal mean number of dates per month in which estimated mean daily flow in the Stamp River was greater than 90 cms (~90th percentile of historic summer flows).

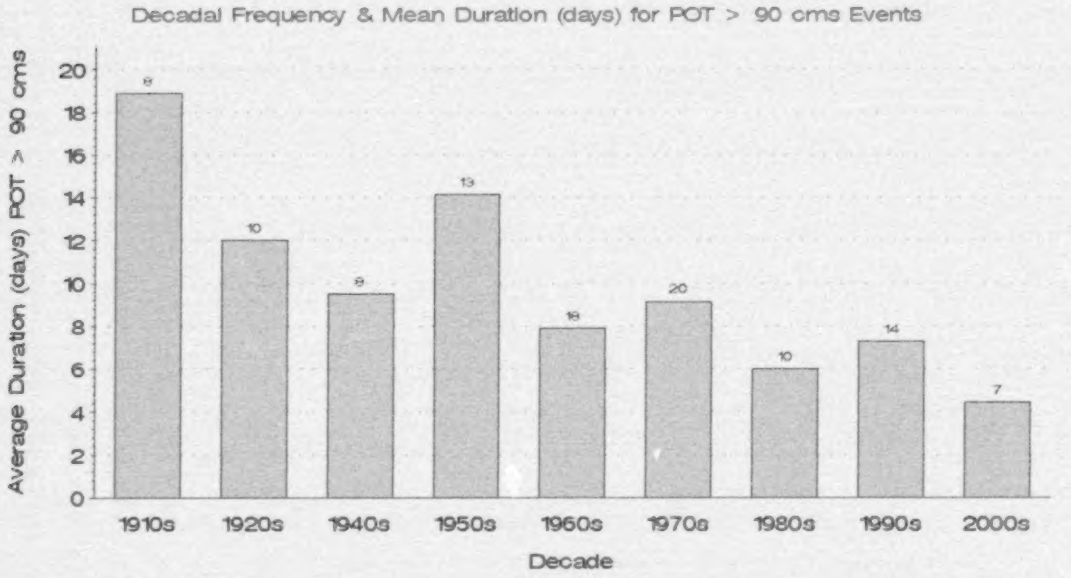


Figure 72. Mean length (days) and mean frequency of number of periods in which estimated mean daily flow in the Stamp River was greater than 90 cms, by decade.

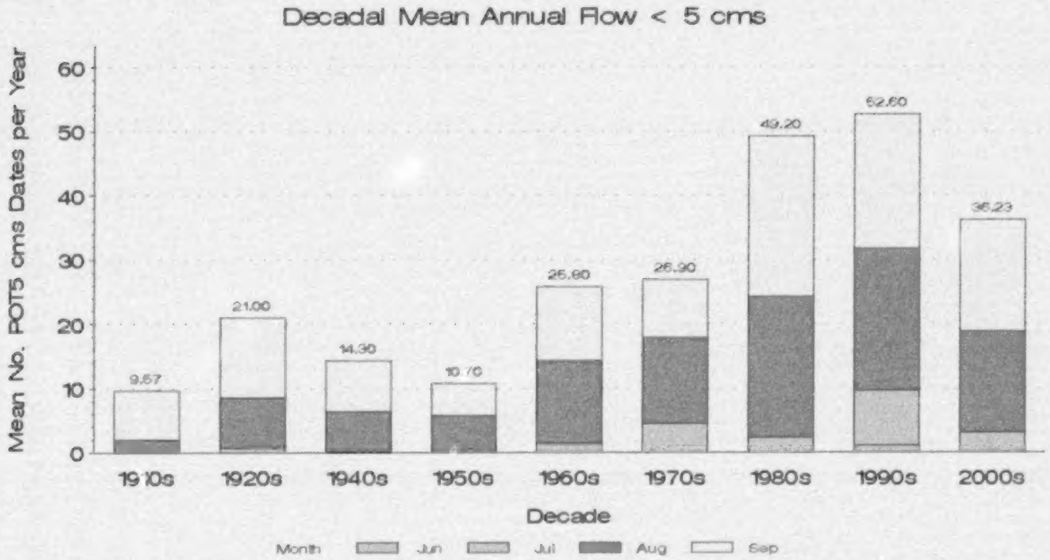


Figure 73. Frequency of decadal mean number of dates per month in which mean daily flow in the Sproat River was less than 5 cms.

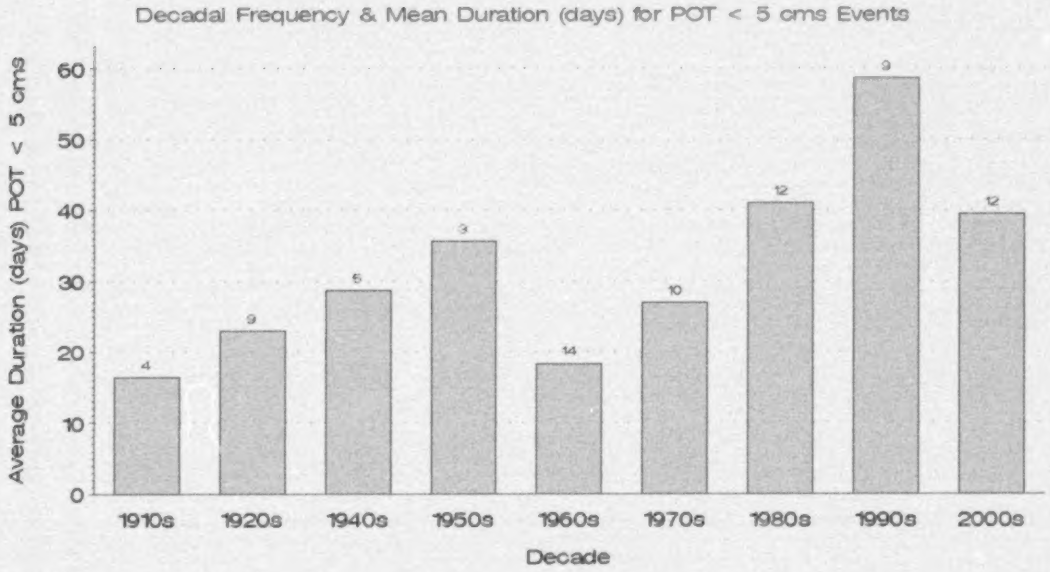


Figure 74. Mean length (days) and mean frequency of number of periods in which mean daily flow in the Sproat River was less than 5 cms, by decade.

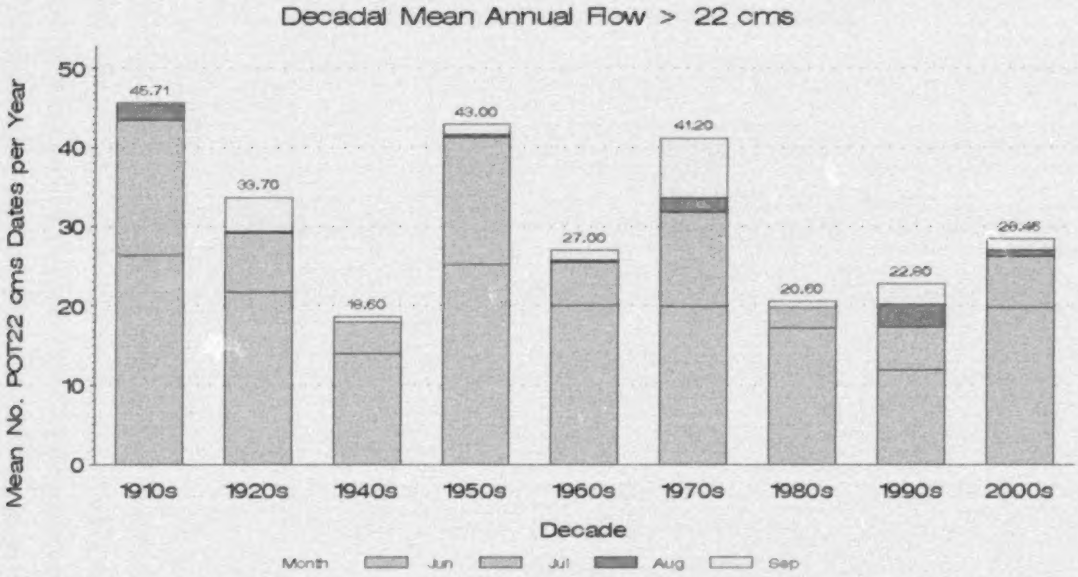


Figure 75. Frequency of decadal mean number of dates per month in which mean daily flow in the Sproat River was greater than 22 cms.

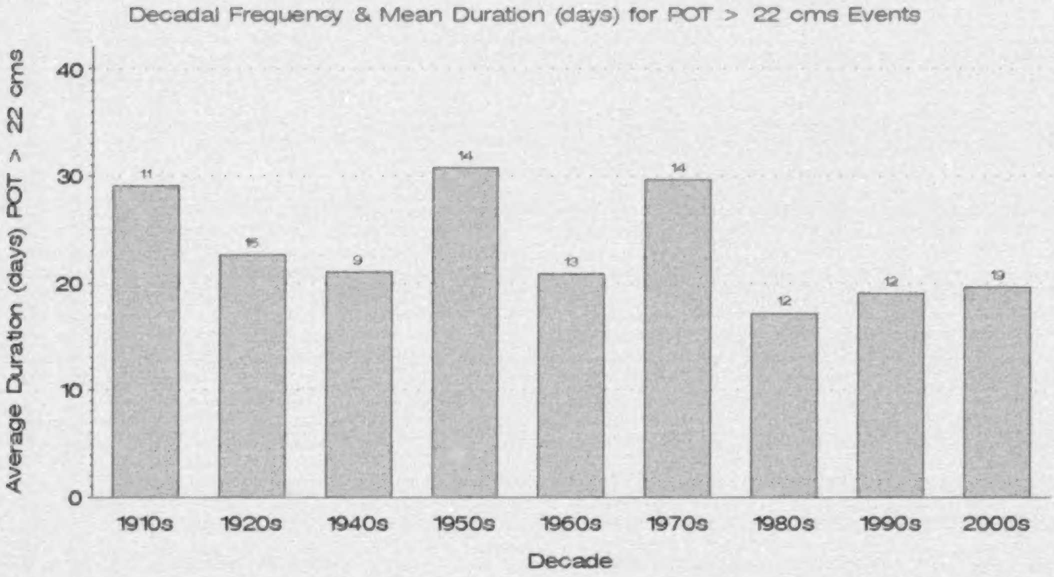
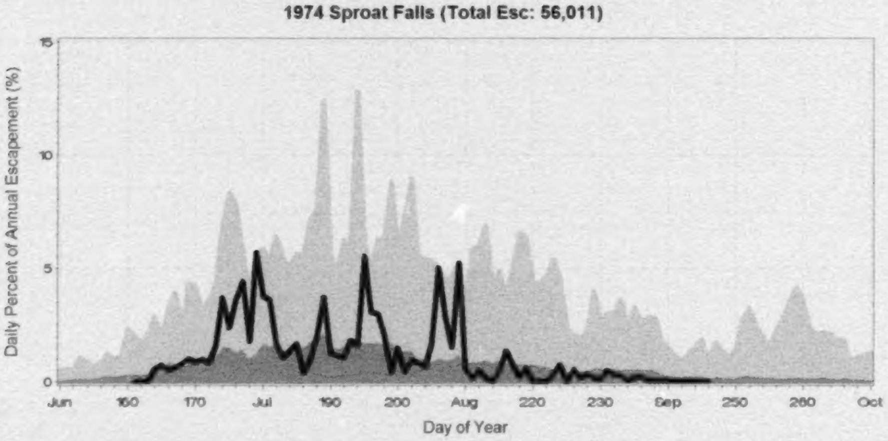


Figure 76. Mean length (days) and mean frequency of number of periods in which mean daily flow in the Sproat River was greater than 22 cms, by decade.

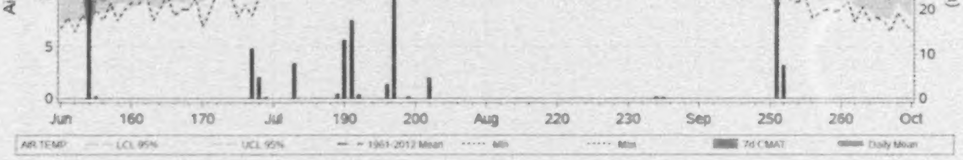
APPENDICES

Appendix A. Multi-panel plots of Sproat and Great Central Lake Sockeye daily migration in relation to environmental variables, by year, 1974-2012.

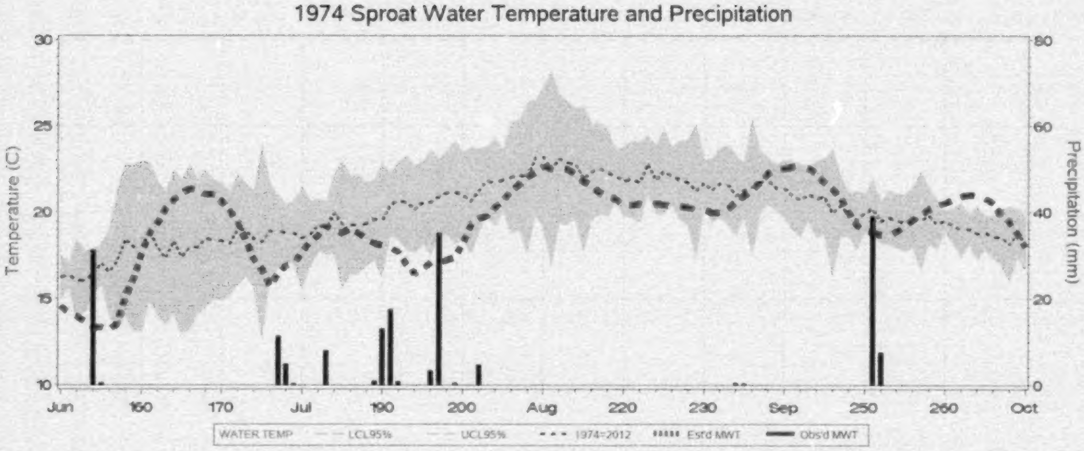
Sample plots (for the year 1974 (below)) include legends with vertical axis variates and horizontal axis with day of year (month label is *approximate* start of each month). Annual plots (following pages) are organized in a multi-panel format for comparison of the following variates:


1974 Sproat Falls (Total Esc: 56,011)

1. Daily migration rates as a percent (%) of annual stock escapement (black line), from daily Sockeye (adult + jack) migrants counted at the GCL/Stamp or Sproat fishways. Historical mean daily migration rate (dark gray area) and maximum daily migration rate (light gray area) for years 1974-2012.

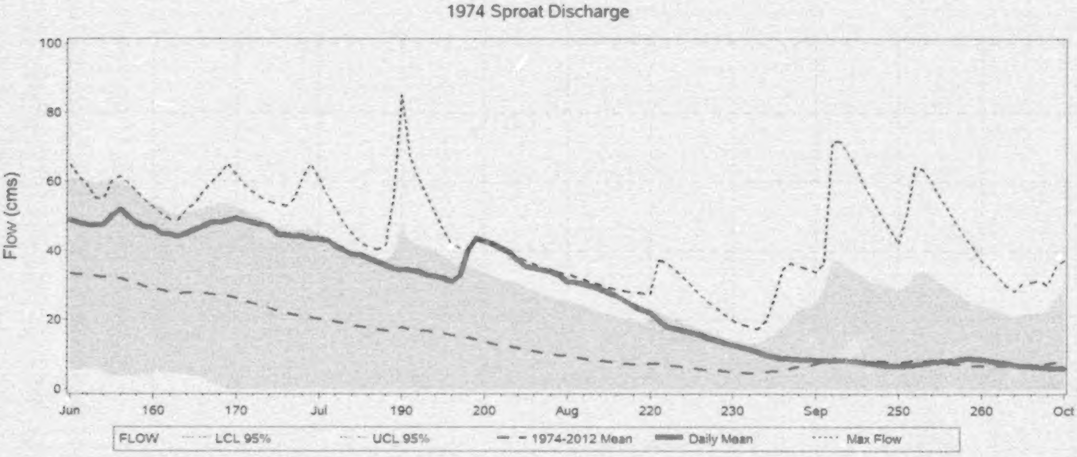

1974 Robertson Creek Station 1030230

2. Precipitation (mm, blue bars), and daily mean air temperature (°C, red line) at ENVIRONMENT CANADA meteorological station *Robertson Creek*, and ROBERTSON CREEK STANDARD (10-day moving average temperature index, grey solid line), with historical daily mean and variance (dashed line and red area), 1911-2012.



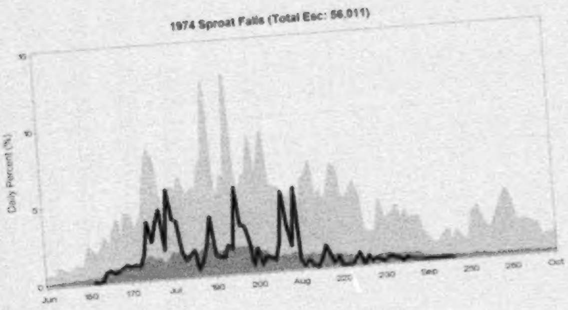
1974 Sproat Water Temperature and Precipitation

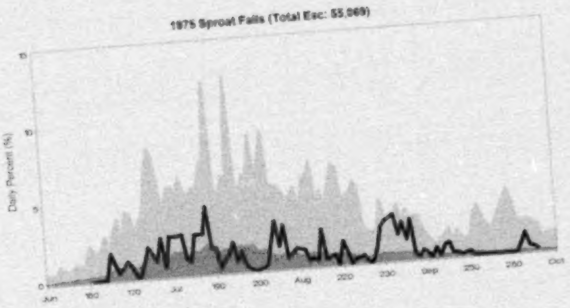
3. Observed (solid blue line) and estimated (dashed blue line) daily mean water temperature at the fishways, with historical water temperature mean and variance (dashed line and gray area); and daily precipitation (black).

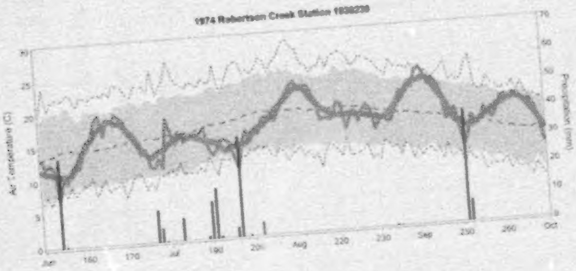


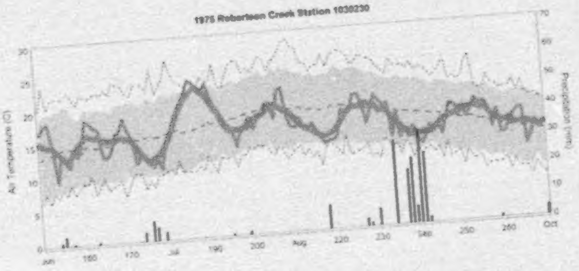
1974 Sproat Discharge

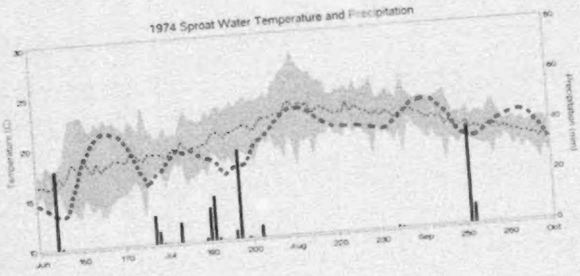
4. Observed or estimated daily mean discharge (cms) at fishways (green line), with historical daily mean and variance (dashed line and green area).

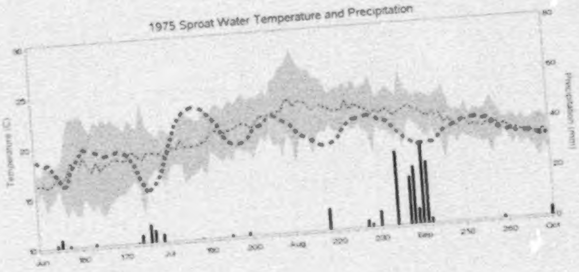

1974 Sproat Falls (Total Esc: 56,011)

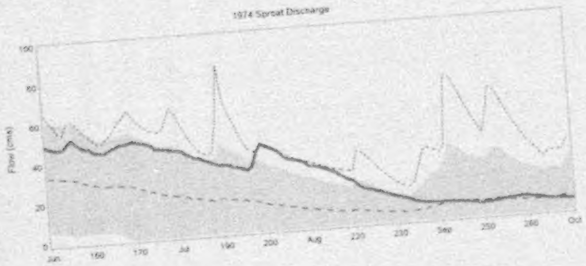

1975 Sproat Falls (Total Esc: 55,969)

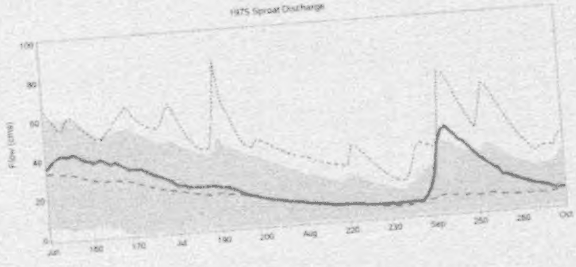

1974 Robertson Creek Station 1030230

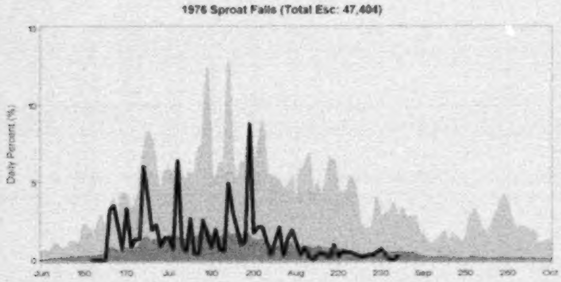

1975 Robertson Creek Station 1030230

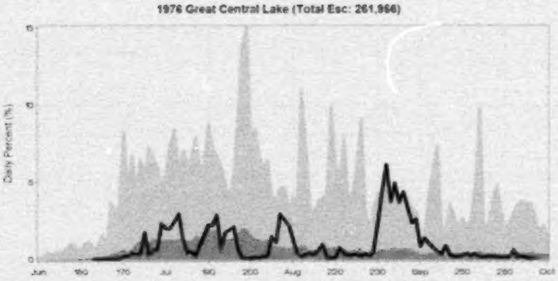

1974 Sproat Water Temperature and Precipitation

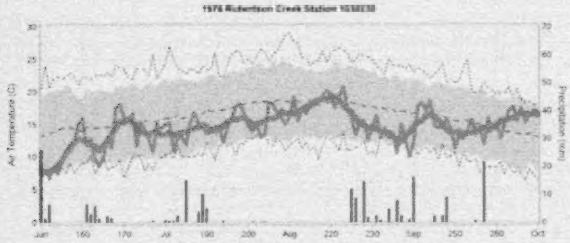

1975 Sproat Water Temperature and Precipitation

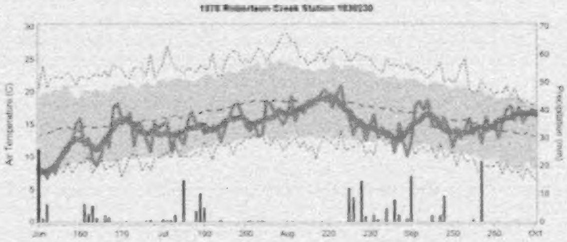

1974 Sproat Discharge

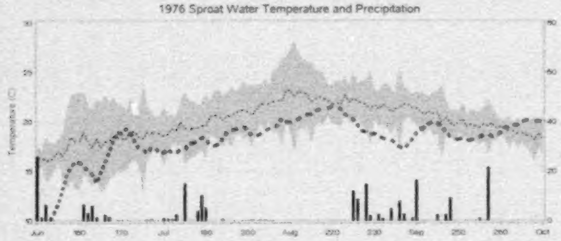

1975 Sproat Discharge

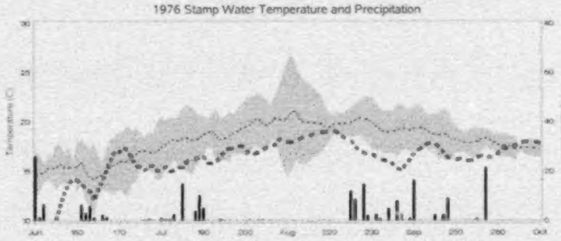

1976 Sproat Falls (Total Esc: 47,404)

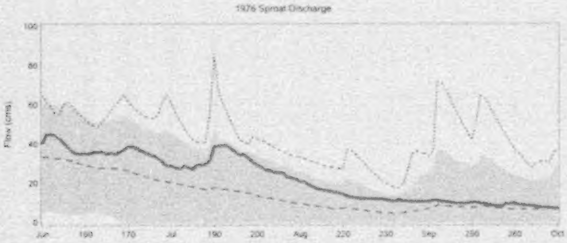

1976 Great Central Lake (Total Esc: 261,966)

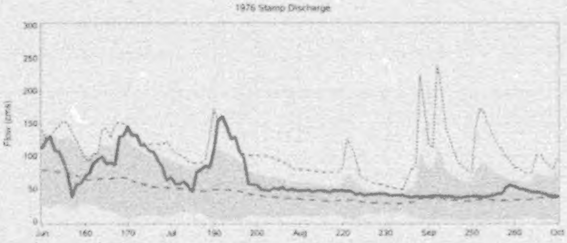

1976 Robertson Creek Station 1030230

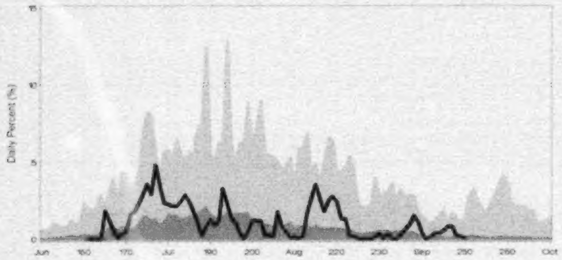

1976 Robertson Creek Station 1030230

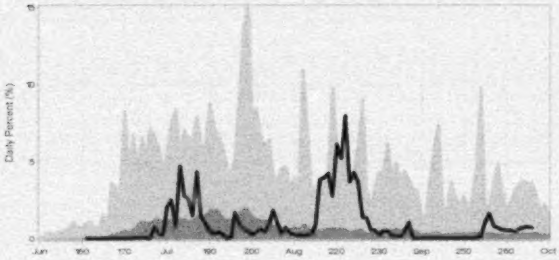

1976 Sproat Water Temperature and Precipitation

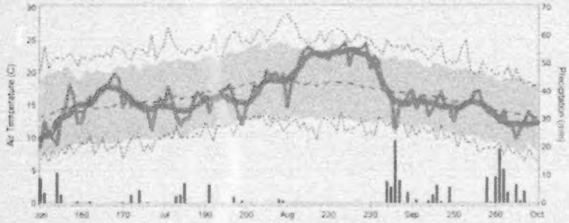

1976 Stamp Water Temperature and Precipitation

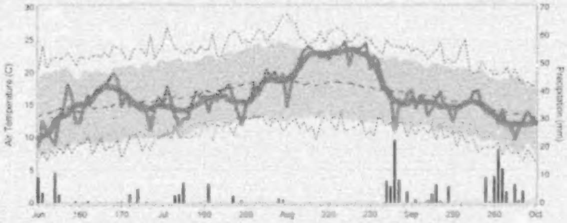

1976 Sproat Discharge

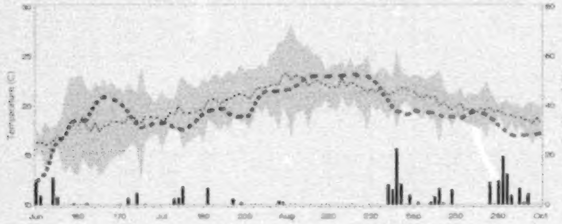

1976 Stamp Discharge

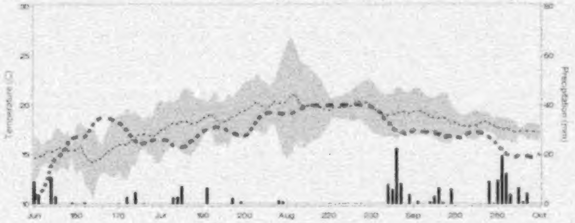

1977 Sproat Falls (Total Esc: 64,219)

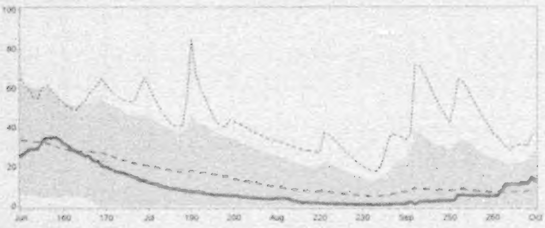

1977 Great Central Lake (Total Esc: 85,933)

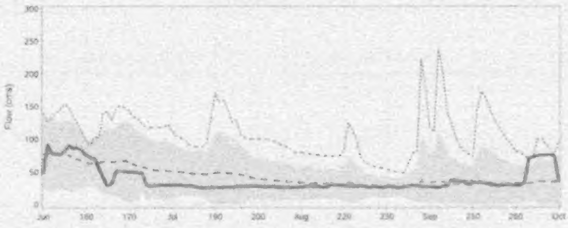

1977 Robertson Creek Station 1030230


1977 Robertson Creek Station 1030230

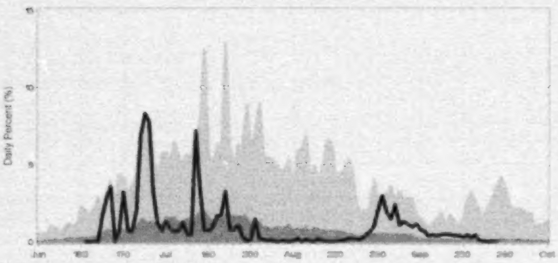

1977 Sproat Water Temperature and Precipitation


1977 Stamp Water Temperature and Precipitation

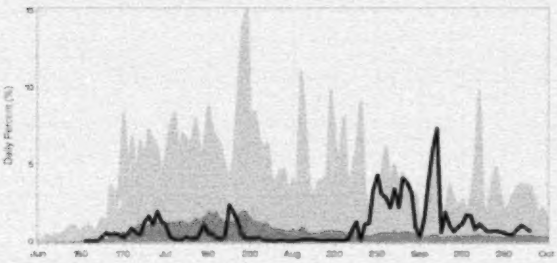

1977 Sproat Discharge


1977 Stamp Discharge

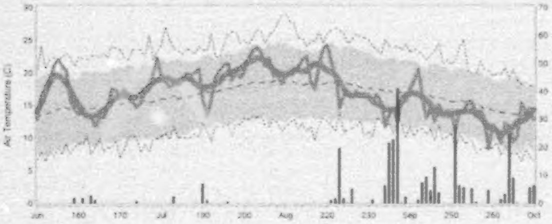
1978 Sproat Falls (Total Esc: 32,580)



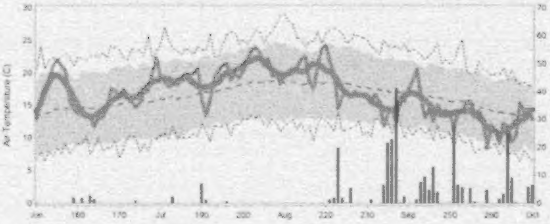
1978 Great Central Lake (Total Esc: 120,442)



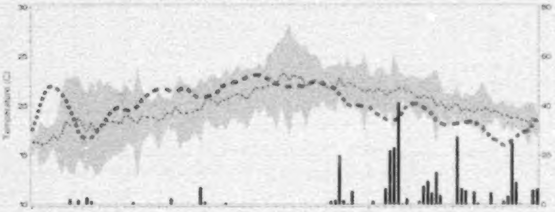
1978 Robertson Creek Station 1030230



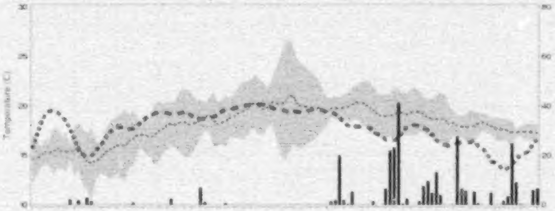
1978 Robertson Creek Station 1030230



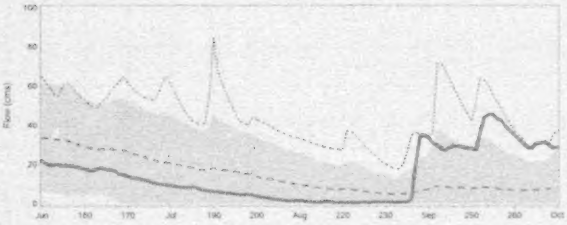
1978 Sproat Water Temperature and Precipitation



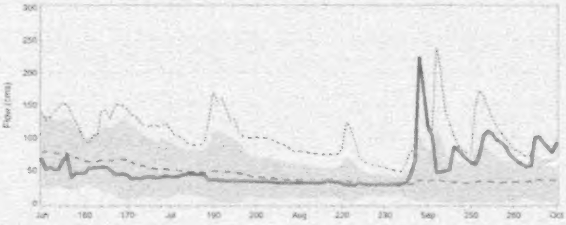
1978 Stamp Water Temperature and Precipitation

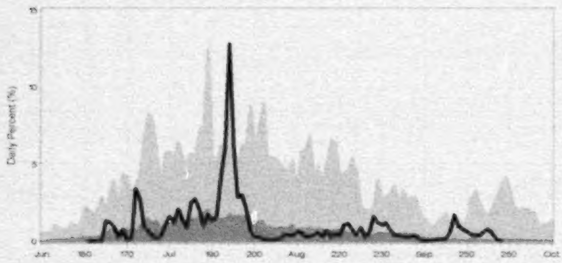


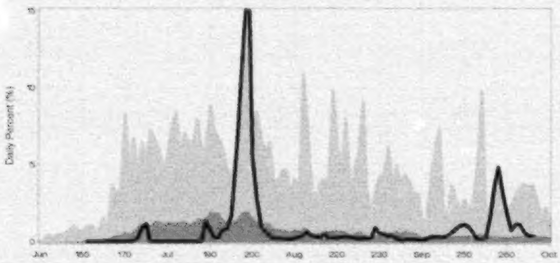
1978 Sproat Discharge

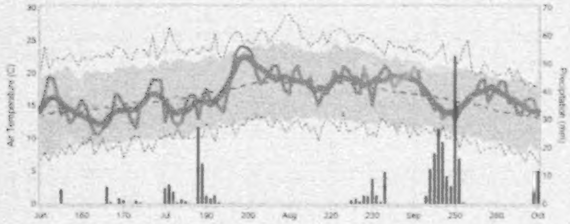


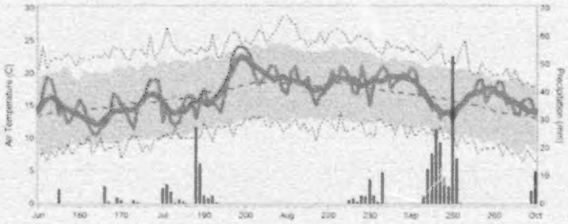
1978 Stamp Discharge

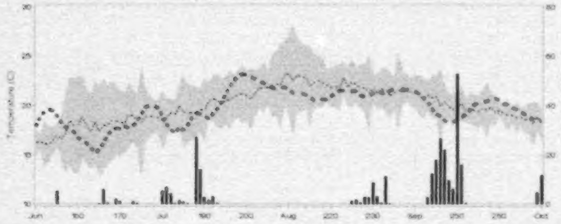


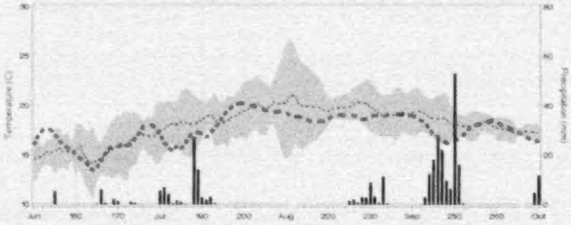

1979 Sproat Falls (Total Esc: 73,473)

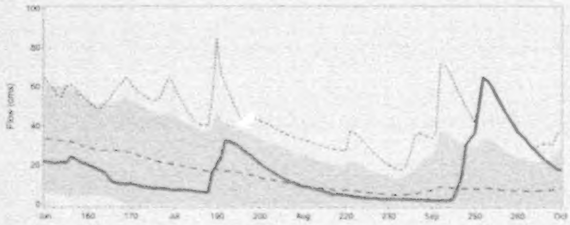

1979 Great Central Lake (Total Esc: 223,264)

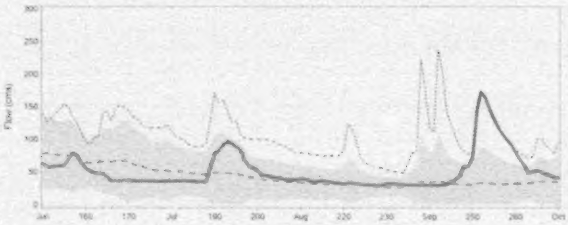

1979 Robertson Creek Station [illegible]

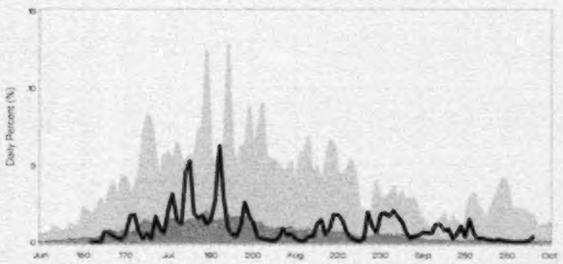

1979 Robertson Creek Station [illegible]

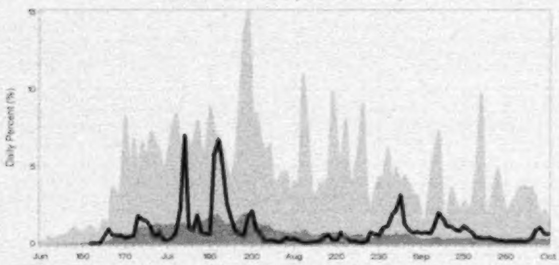

1979 Sproat Water Temperature and Precipitation

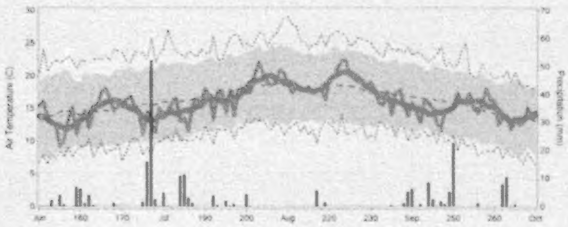

1979 Stamp Water Temperature and Precipitation

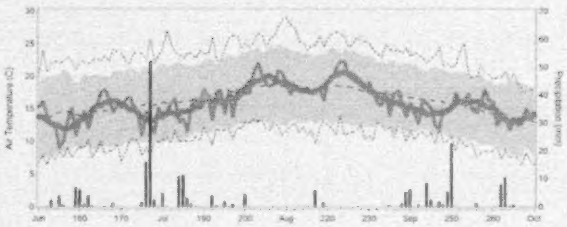

1979 Sproat Discharge

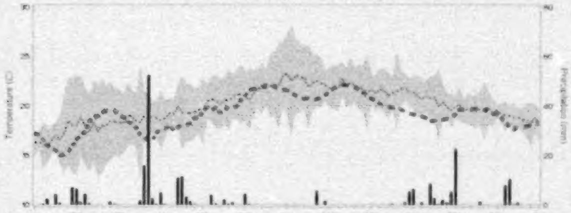

1979 Stamp Discharge

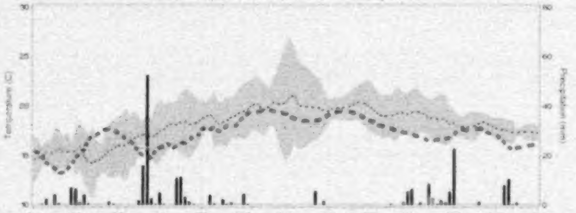

1980 Sproat Falls (Total Esc: 136,033)

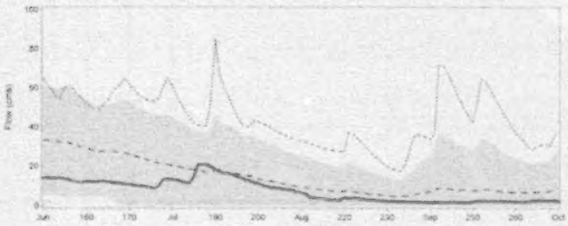

1980 Great Central Lake (Total Esc: 165,168)

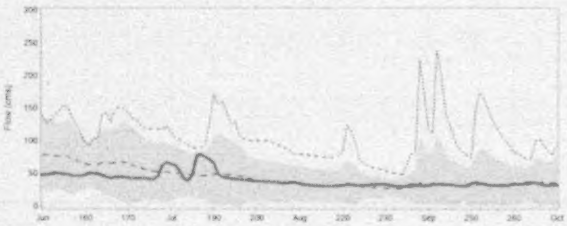

1980 Robertson Creek Station 1030230

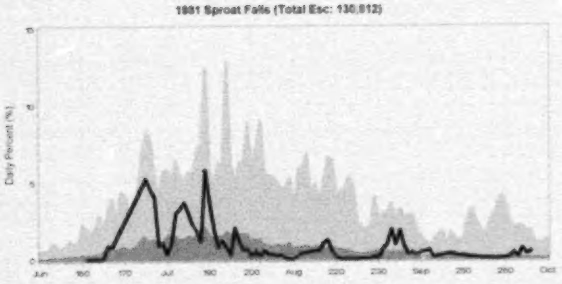

1980 Robertson Creek Station 1030230

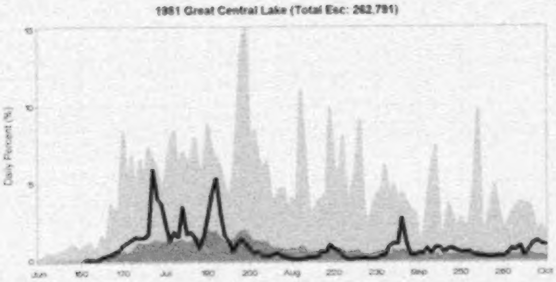

1980 Sproat Water Temperature and Precipitation

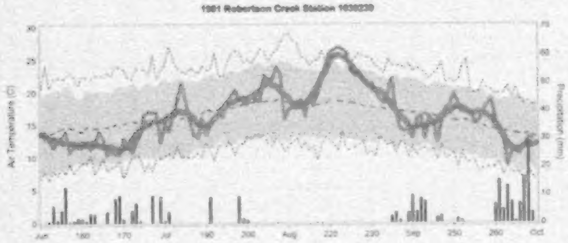

1980 Stamp Water Temperature and Precipitation

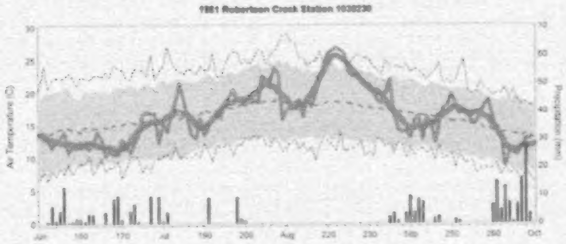

1980 Sproat Discharge

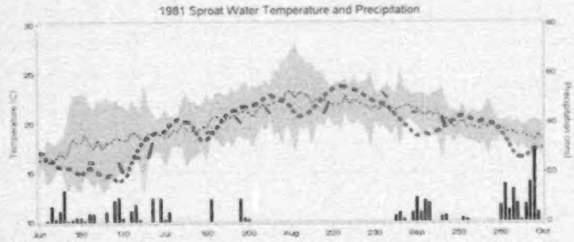

1980 Stamp Discharge

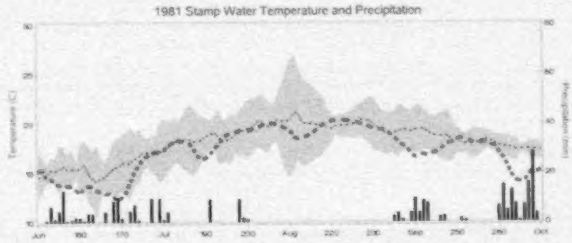

1981 Sproat Falls (Total Esc: 130,812)

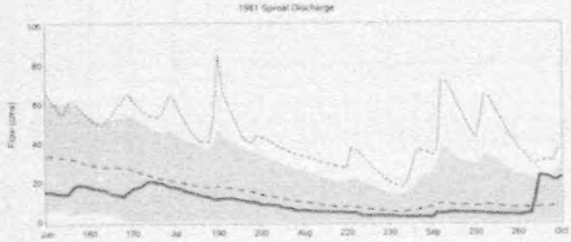

1981 Great Central Lake (Total Esc: 262,791)

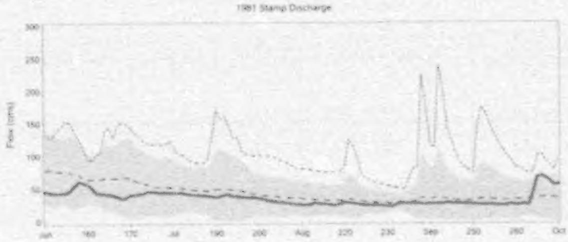

1981 Robertson Creek Station 1030230

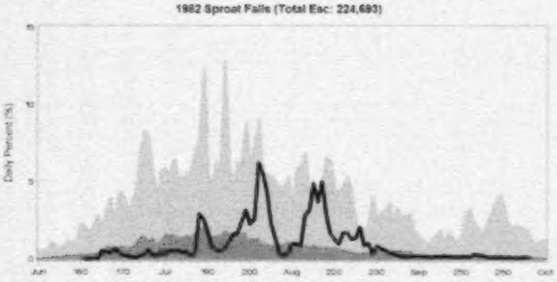

1981 Robertson Creek Station 1030230

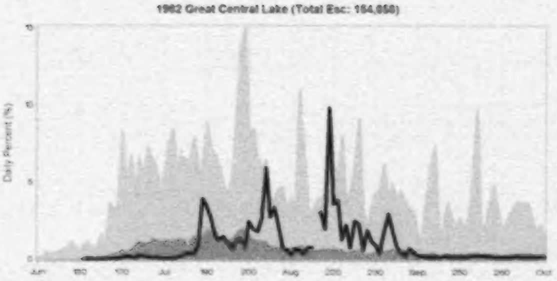

1981 Sproat Water Temperature and Precipitation

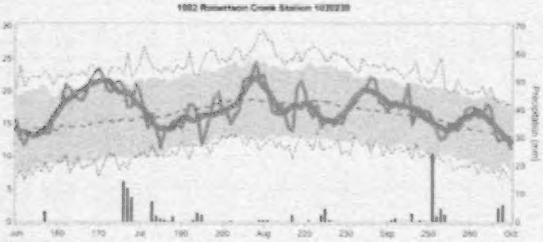

1981 Stamp Water Temperature and Precipitation

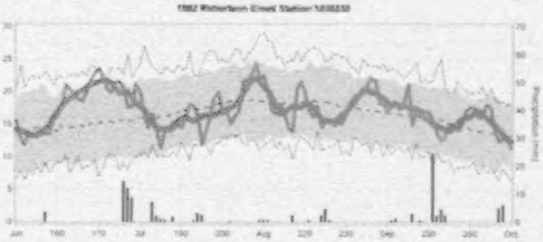

1981 Sproat Discharge

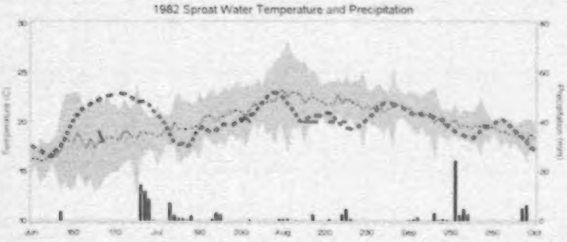

1981 Stamp Discharge

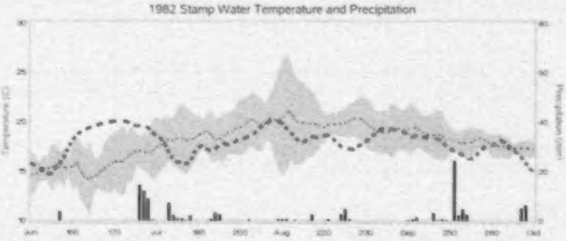

1982 Sproat Falls (Total Esc: 224,693)
Daily Percent (%)
Jun
Jul
Aug
Sep
Oct

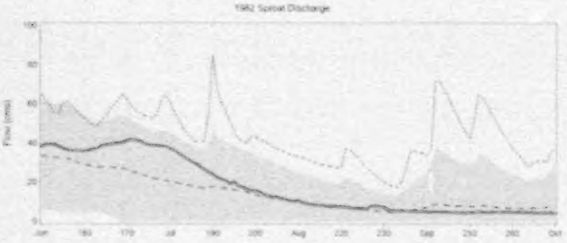

1982 Great Central Lake (Total Esc: 154,858)
Daily Percent (%)
Jun
Jul
Aug
Sep
Oct

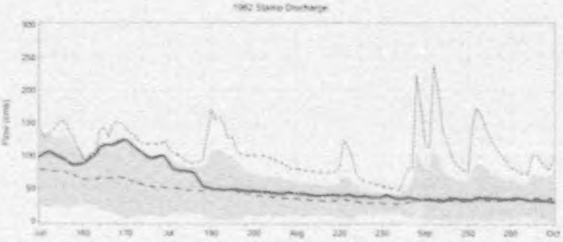

1982 Robertson Creek Station 1030230
Air Temperature (C)
Precipitation (mm)
Jun
Jul
Aug
Sep
Oct

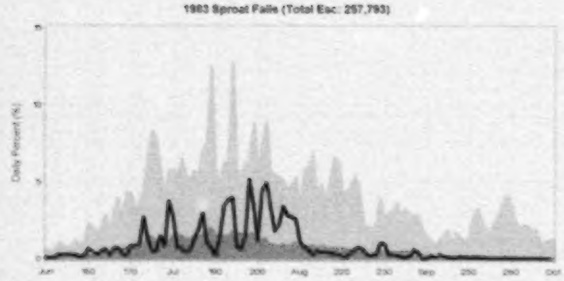

1982 Robertson Creek Station 1030230
Air Temperature (C)
Precipitation (mm)
Jun
Jul
Aug
Sep
Oct

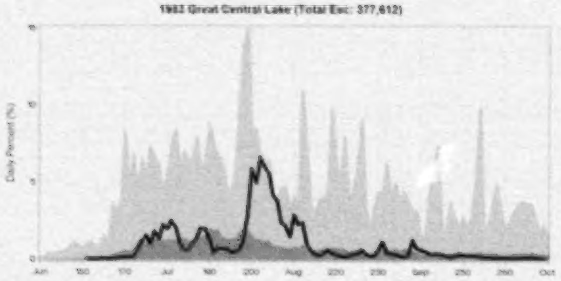

1982 Sproat Water Temperature and Precipitation
Temperature (C)
Precipitation (mm)
Jun
Jul
Aug
Sep
Oct

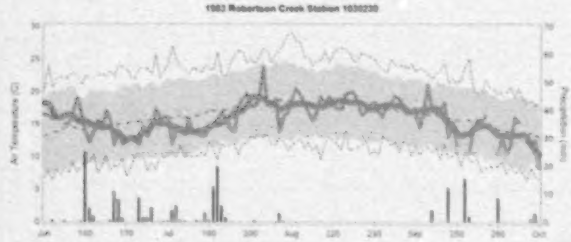

1982 Stamp Water Temperature and Precipitation
Temperature (C)
Precipitation (mm)
Jun
Jul
Aug
Sep
Oct

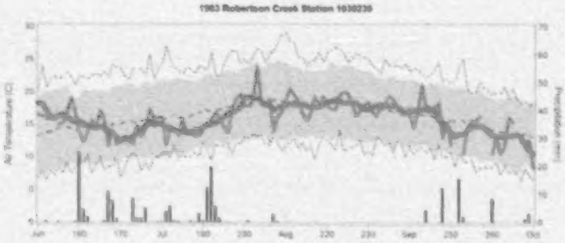

1982 Sproat Discharge
Flow (cms)
Jun
Jul
Aug
Sep
Oct

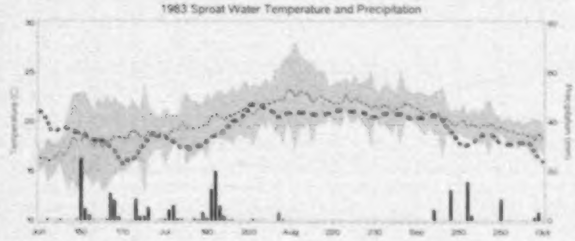

1982 Stamp Discharge
Flow (cms)
Jun
Jul
Aug
Sep
Oct

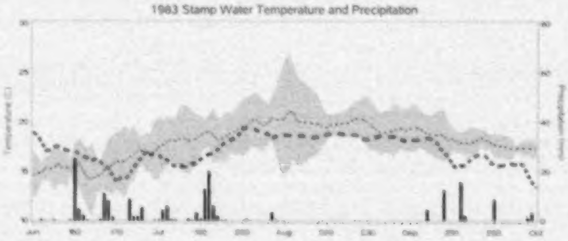

1983 Sproat Falls (Total Esc: 257,793)
Daily Percent (%)
Jun
160
170
Jul
190
200
Aug
220
230
Sep
250
260
Oct

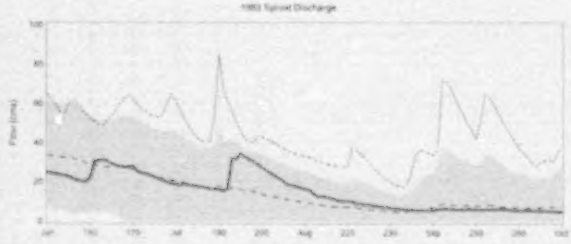

1983 Great Central Lake (Total Esc: 377,612)
Daily Percent (%)
Jun
160
170
Jul
190
200
Aug
220
230
Sep
250
260
Oct

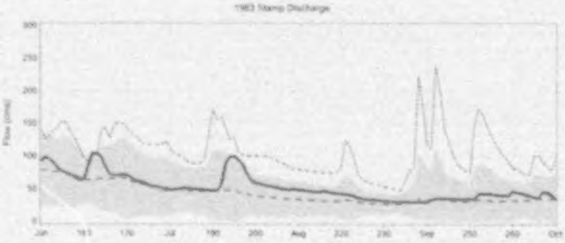

1983 Robertson Creek Station 1030230
Air Temperature (C)
Precipitation (mm)

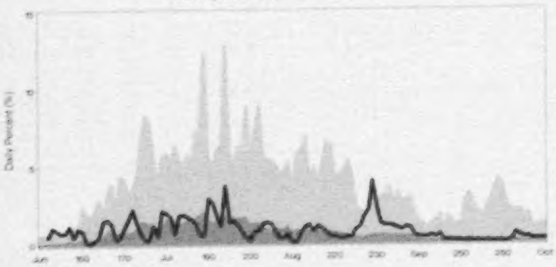

1983 Robertson Creek Station 1030230
Air Temperature (C)
Precipitation (mm)

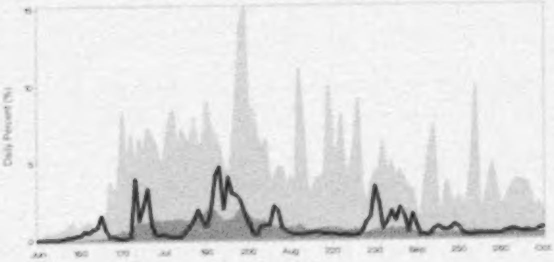

1983 Sproat Water Temperature and Precipitation
Temperature (C)
Precipitation (mm)

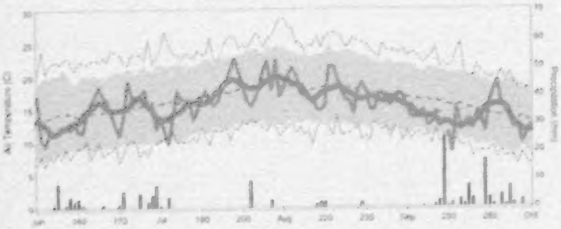

1983 Stamp Water Temperature and Precipitation
Temperature (C)
Precipitation (mm)

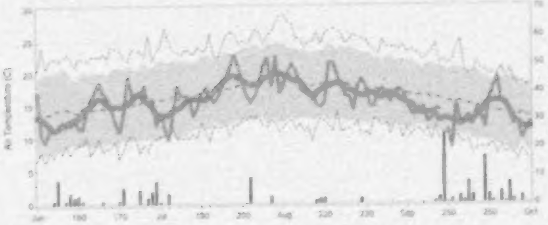

1983 Sproat Discharge
Flow (cms)

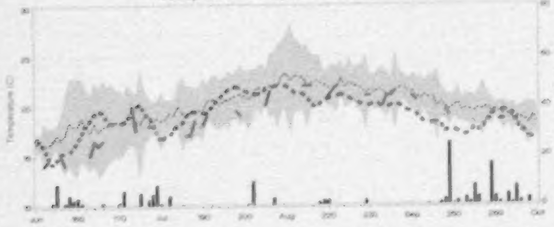

1983 Stamp Discharge
Flow (cms)

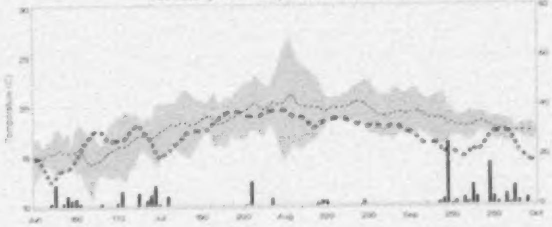

1984 Sproat Falls (Total Esc: 89,100)

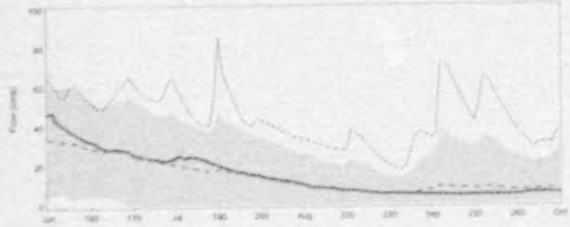

1984 Great Central Lake (Total Esc: 133,310)

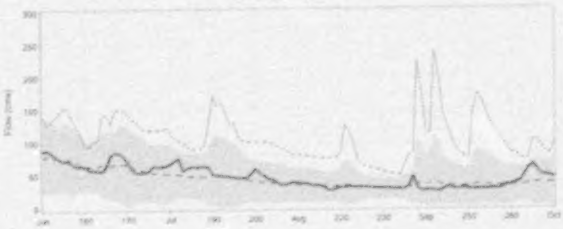

1984 Robertson Creek Station 1030230

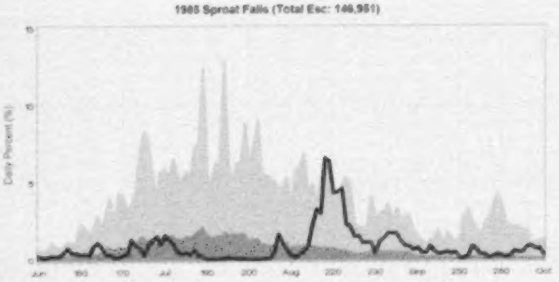

1984 Robertson Creek Station 1030230


1984 Sproat Water Temperature and Precipitation

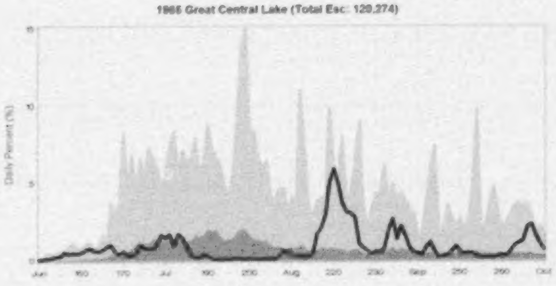

1984 Stamp Water Temperature and Precipitation


1984 Sproat Discharge

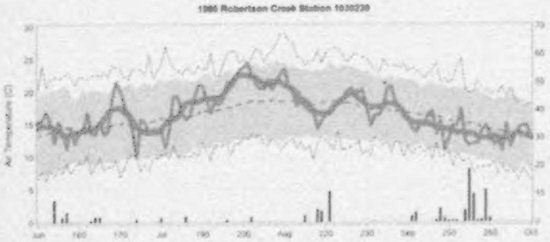

1984 Stamp Discharge



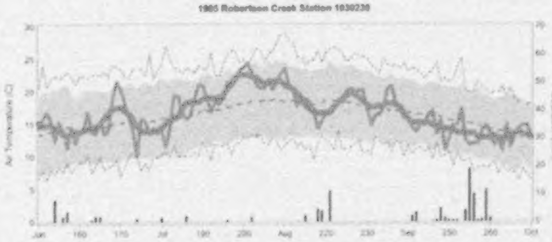
1985 Sproat Falls (Total Esc: 146,951)



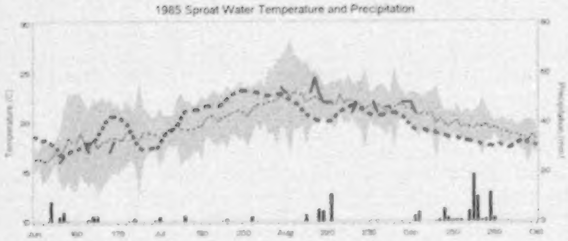
1985 Great Central Lake (Total Esc: 120,274)



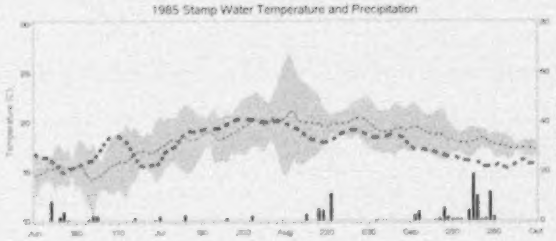
1985 Robertson Creek Station 1030230



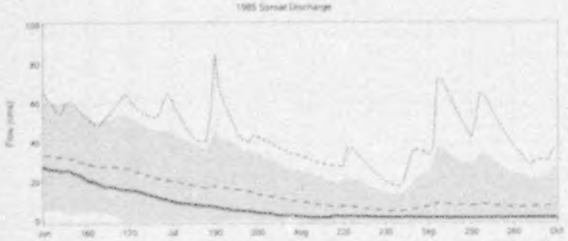
1985 Robertson Creek Station 1030230



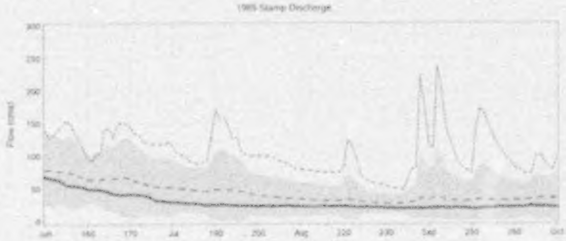
1985 Sproat Water Temperature and Precipitation



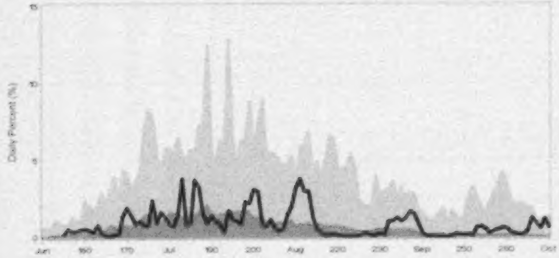
1985 Stamp Water Temperature and Precipitation

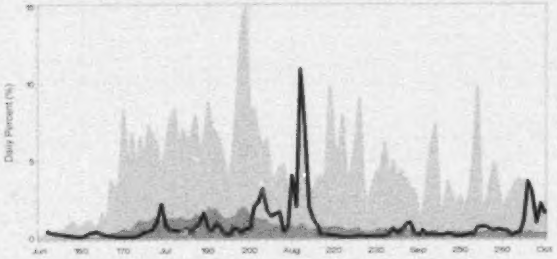


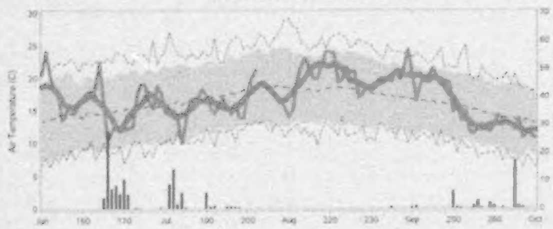
1985 Sproat Discharge

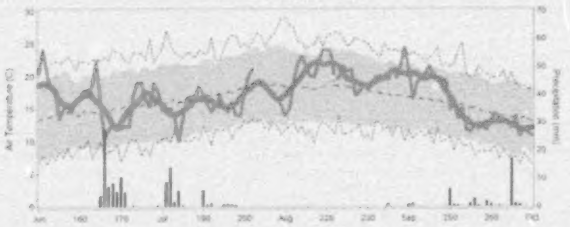


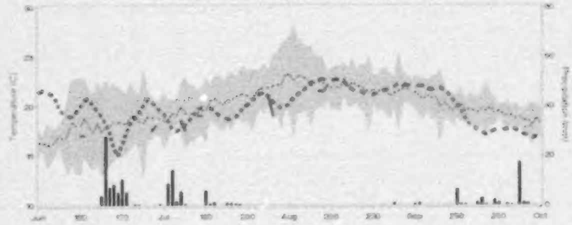
1985 Stamp Discharge

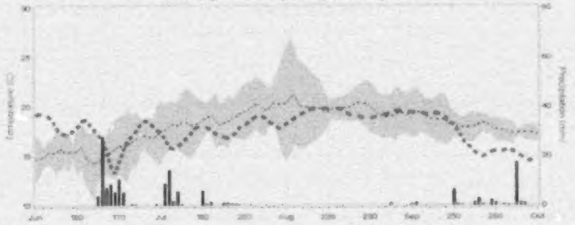

1986 Sproat Falls (Total Esc: 192,941)

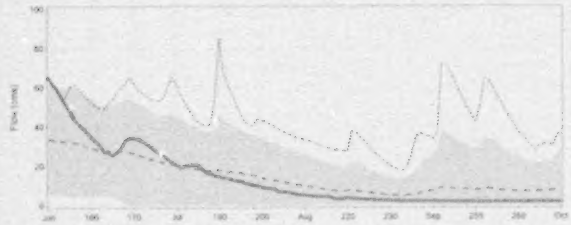

1986 Great Central Lake (Total Esc: 137,807)

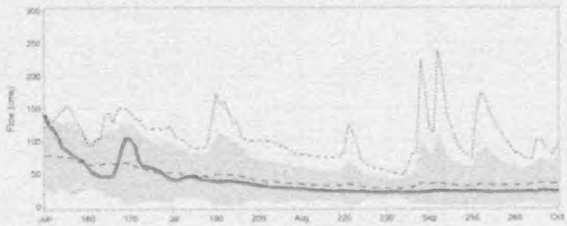

1986 Robertson Creek Station 1030230

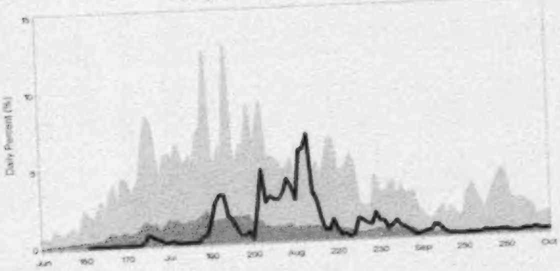

1986 Robertson Creek Station 1030230


1986 Sproat Water Temperature and Precipitation

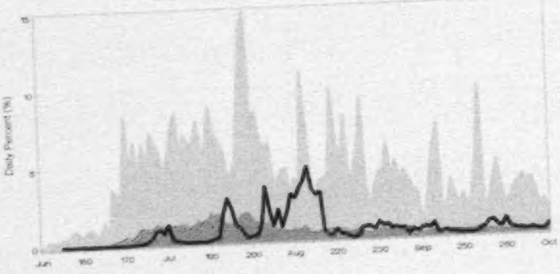

1986 Stamp Water Temperature and Precipitation


1986 Sproat Discharge

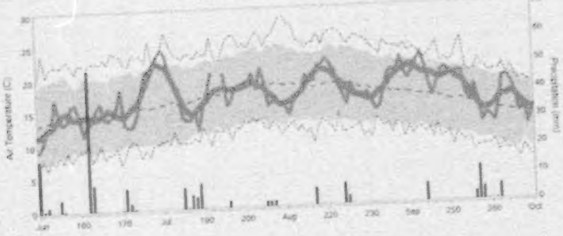

1986 Stamp Discharge



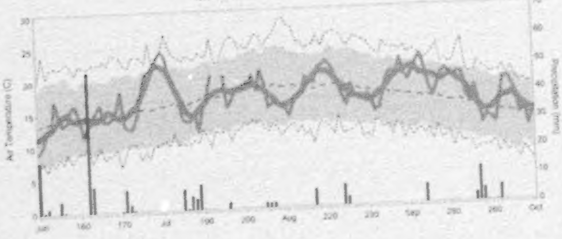
1987 Sproat Falls (Total Esc: 151,835)



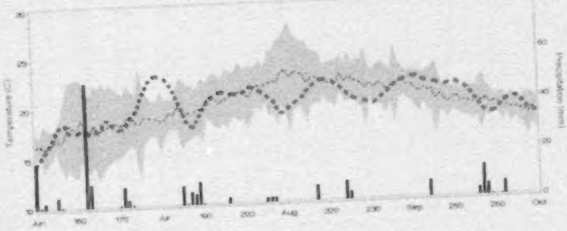
1987 Great Central Lake (Total Esc: 290,716)



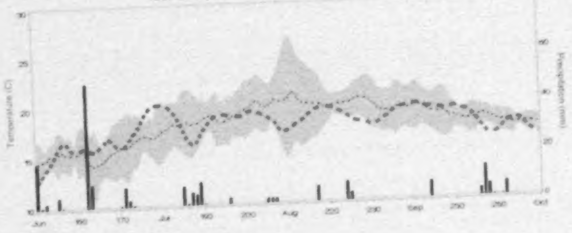
1987 Robertson Creek Station 1030230



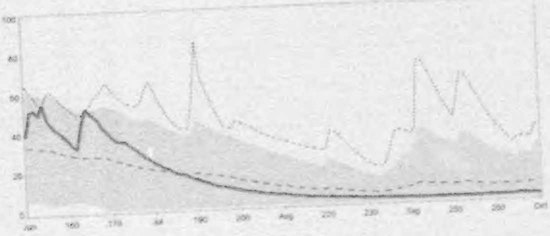
1987 Robertson Creek Station 1030230



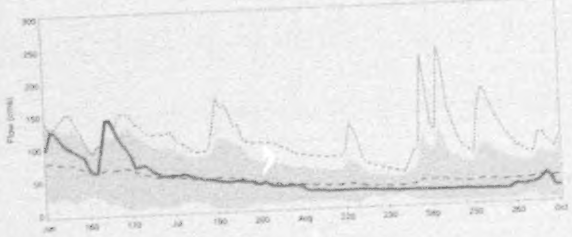
1987 Sproat Water Temperature and Precipitation



1987 Stamp Water Temperature and Precipitation

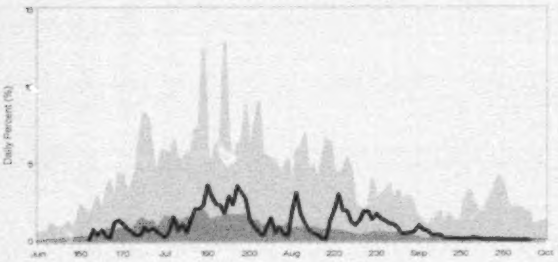


1987 Sproat Discharge

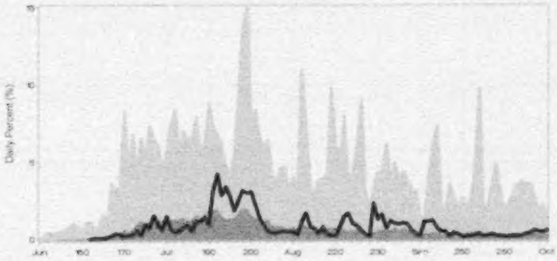


1987 Stamp Discharge

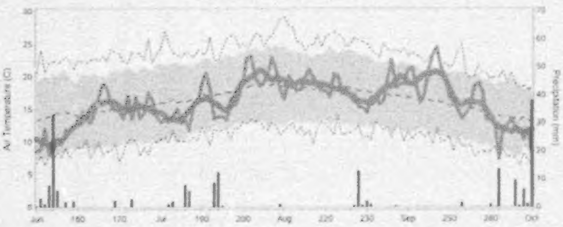
1988 Sproat Falls (Total Esc: 235,417)



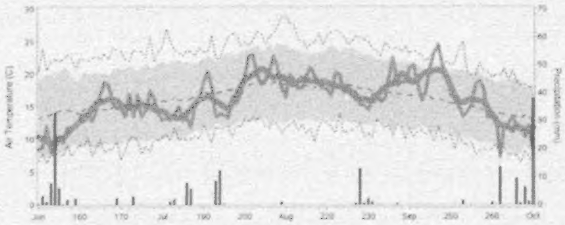
1988 Great Central Lake (Total Esc: 206,676)



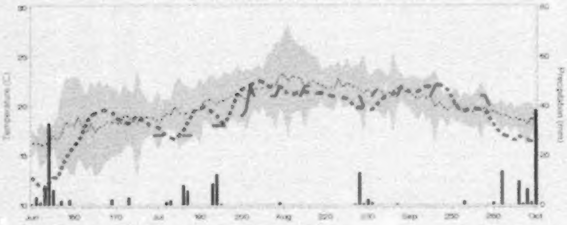
1988 Robertson Creek Station 1030230



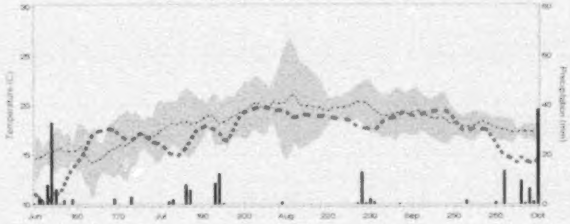
1988 Robertson Creek Station 1030230



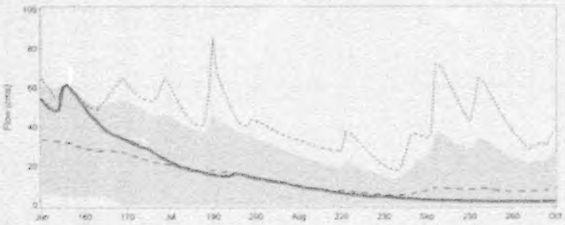
1988 Sproat Water Temperature and Precipitation



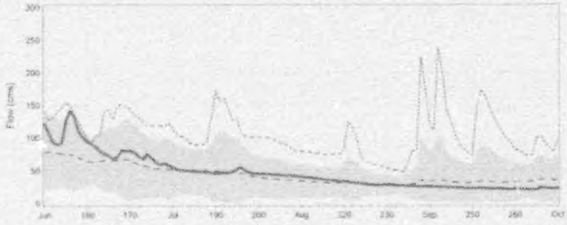
1988 Stamp Water Temperature and Precipitation

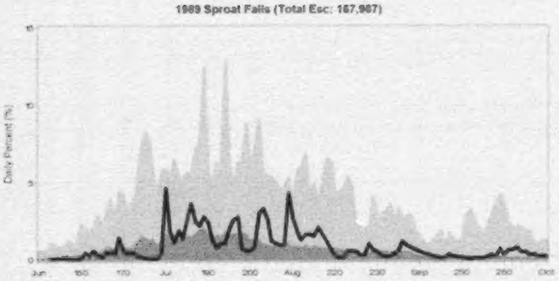


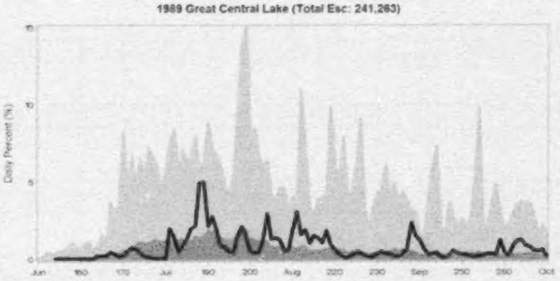
1988 Sproat Discharge

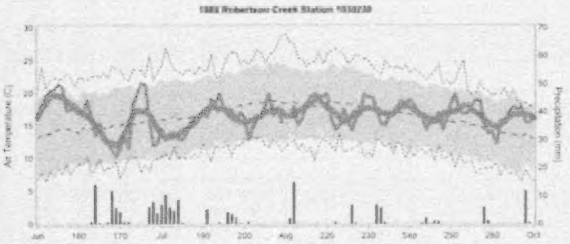


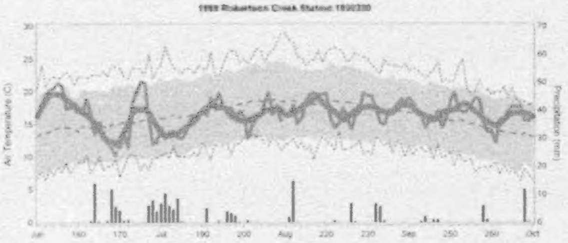
1988 Stamp Discharge

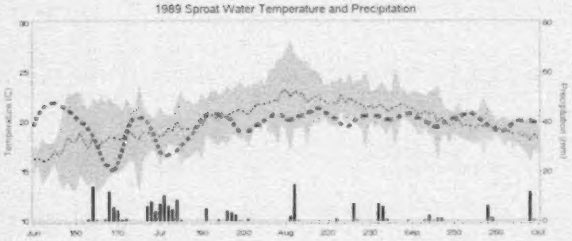


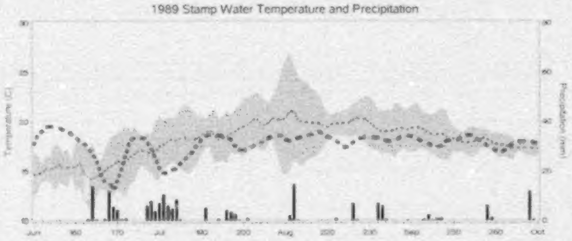

1989 Sproat Falls (Total Esc: 167,987)
Daily Percent (%)
0
5
10
15
Jun
160
170
Jul
190
200
Aug
220
230
Sep
250
260
Oct

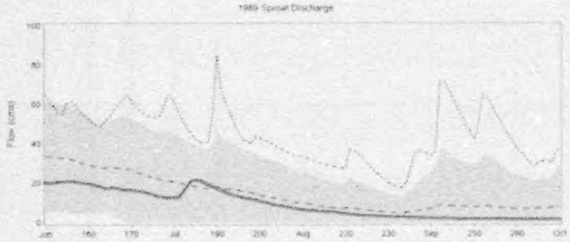

1989 Great Central Lake (Total Esc: 241,263)
Daily Percent (%)
0
5
10
15
Jun
160
170
Jul
190
200
Aug
220
230
Sep
250
260
Oct

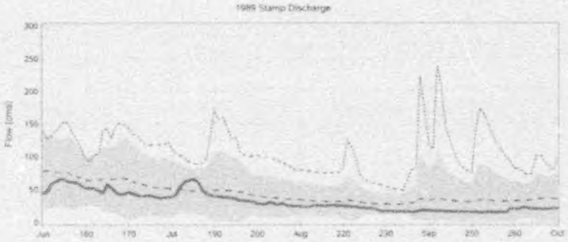

1989 Robertson Creek Station 1030230
Air Temperature (C)
Precipitation (mm)
0
5
10
15
20
25
30
70
60
50
40
30
20
10
Jun
160
170
Jul
190
200
Aug
220
230
Sep
250
260
Oct

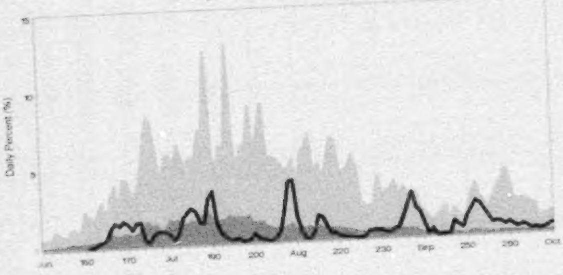

1989 Robertson Creek Station 1030230
Air Temperature (C)
Precipitation (mm)
0
5
10
15
20
25
30
70
60
50
40
30
20
10
Jun
160
170
Jul
190
200
Aug
220
230
Sep
250
260
Oct


1989 Sproat Water Temperature and Precipitation
Temperature (C)
Precipitation (mm)
10
15
20
25
30
0
20
40
60
80
Jun
160
170
Jul
190
200
Aug
220
230
Sep
250
260
Oct

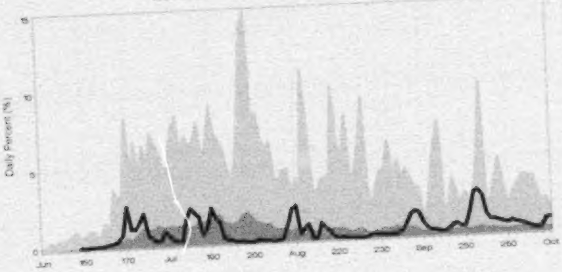

1989 Stamp Water Temperature and Precipitation
Temperature (C)
Precipitation (mm)
10
15
20
25
30
0
20
40
60
80
Jun
160
170
Jul
190
200
Aug
220
230
Sep
250
260
Oct


1989 Sproat Discharge
Flow (cms)
0
20
40
60
80
100
Jun
160
170
Jul
190
200
Aug
220
230
Sep
250
260
Oct

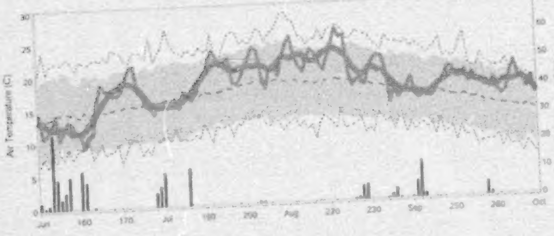

1989 Stamp Discharge
Flow (cms)
0
50
100
150
200
250
300
Jun
160
170
Jul
190
200
Aug
220
230
Sep
250
260
Oct



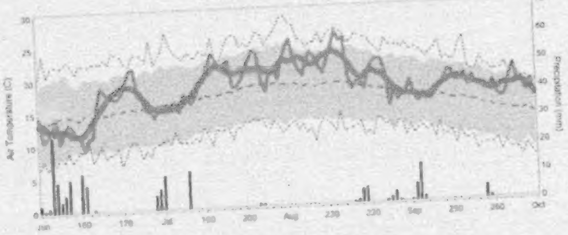
1990 Sproat Falls (Total Esc: 112,780)



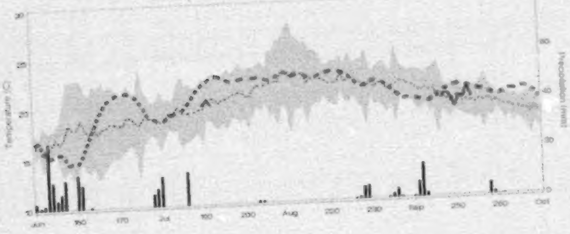
1990 Great Central Lake (Total Esc: 179,604)



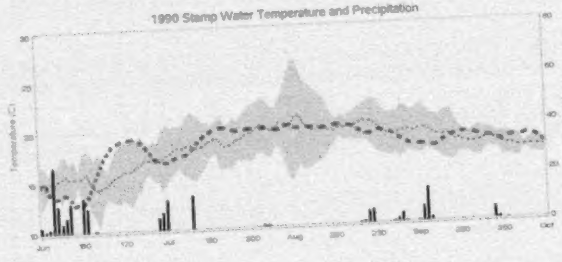
1990 Robertson Creek Station 1030230



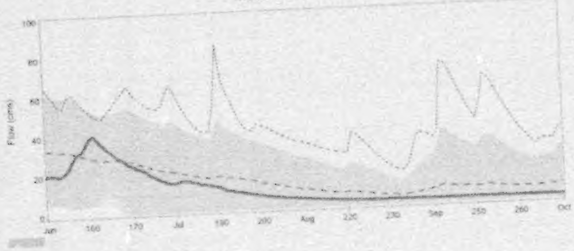
1990 Robertson Creek Station 1030230



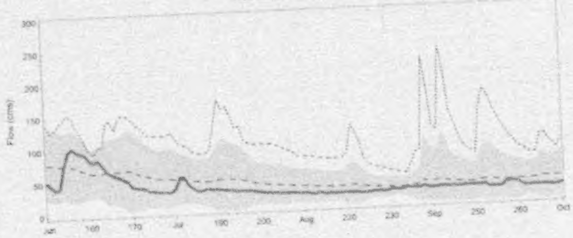
1990 Sproat Water Temperature and Precipitation



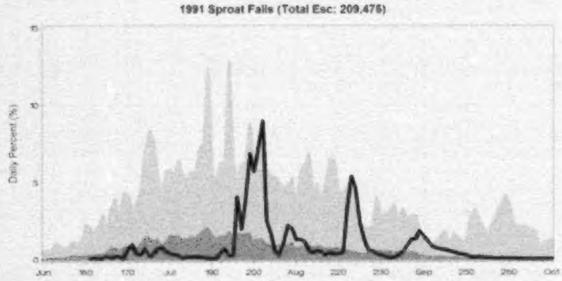
1990 Stamp Water Temperature and Precipitation

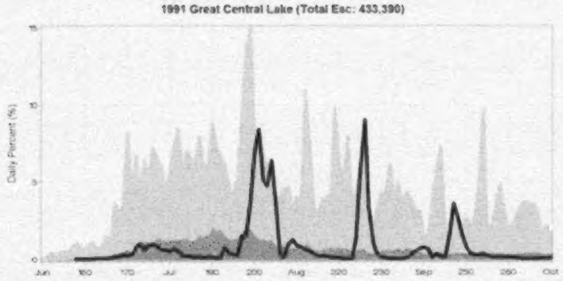


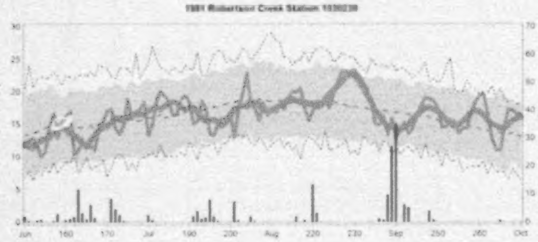
1990 Sproat Discharge

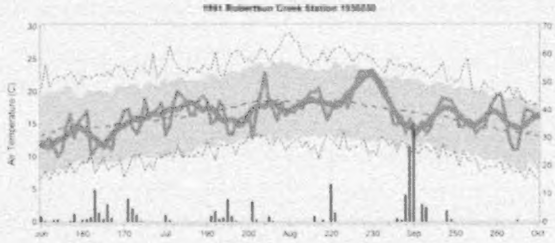


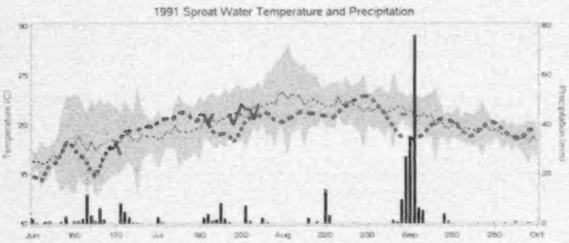
1990 Stamp Discharge

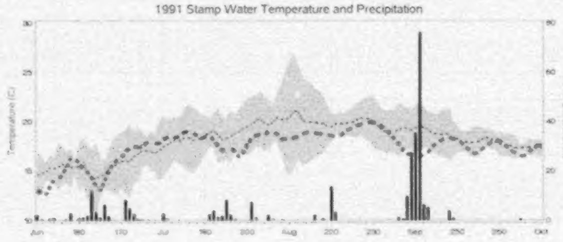

1991 Sproat Falls (Total Esc: 209,476)
Daily Percent (%)
Jun
Jul
Aug
Sep
Oct

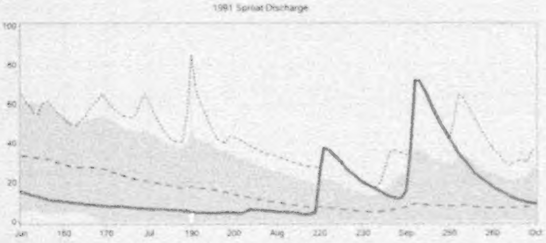

1991 Great Central Lake (Total Esc: 433,390)
Daily Percent (%)
Jun
Jul
Aug
Sep
Oct

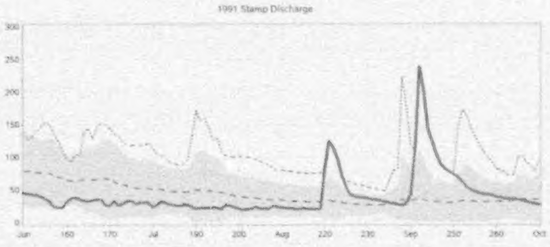

1991 Robertson Creek Station 1030230
Air Temperature (C)
Precipitation (mm)
Jun
Jul
Aug
Sep
Oct

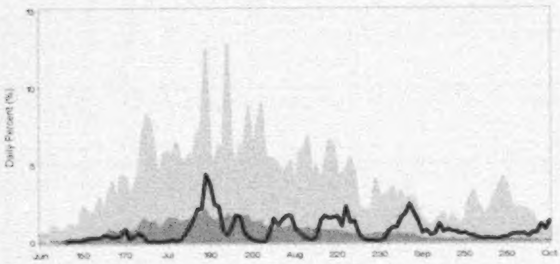

1991 Robertson Creek Station 1030230
Air Temperature (C)
Precipitation (mm)
Jun
Jul
Aug
Sep
Oct

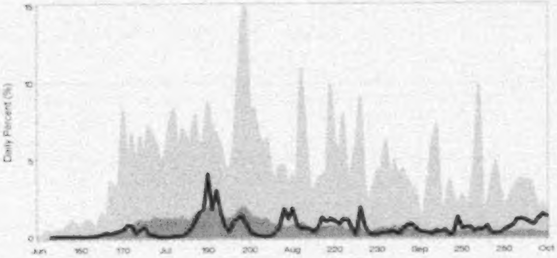

1991 Sproat Water Temperature and Precipitation
Temperature (C)
Precipitation (mm)
Jun
Jul
Aug
Sep
Oct

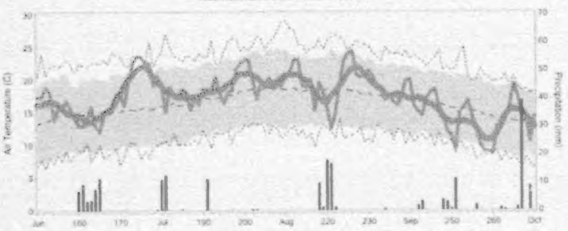

1991 Stamp Water Temperature and Precipitation
Temperature (C)
Precipitation (mm)
Jun
Jul
Aug
Sep
Oct

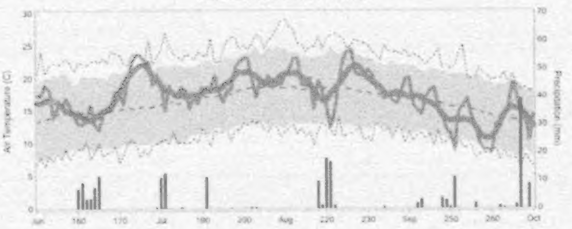

1991 Sproat Discharge
Flow (cms)
Jun
Jul
Aug
Sep
Oct

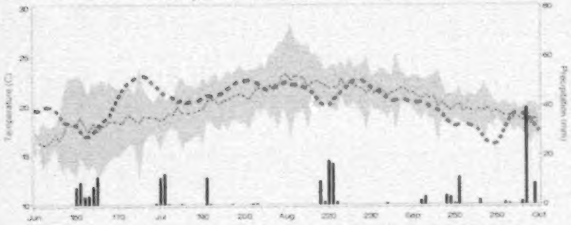

1991 Stamp Discharge
Flow (cms)
Jun
Jul
Aug
Sep
Oct

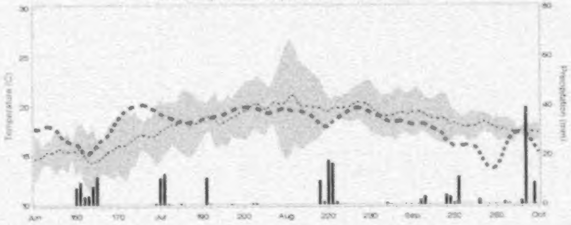

1992 Sproat Falls (Total Esc: 221,938)

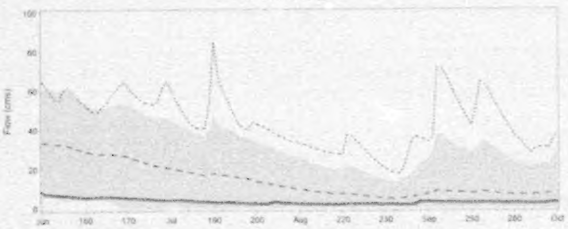

1992 Great Central Lake (Total Esc: 195,118)

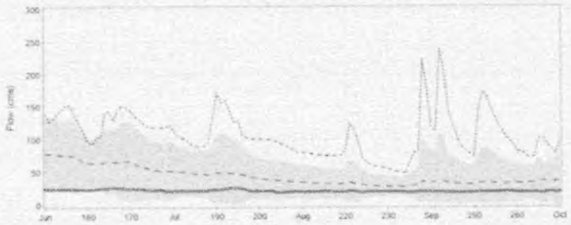

1992 Robertson Creek Station 1030230

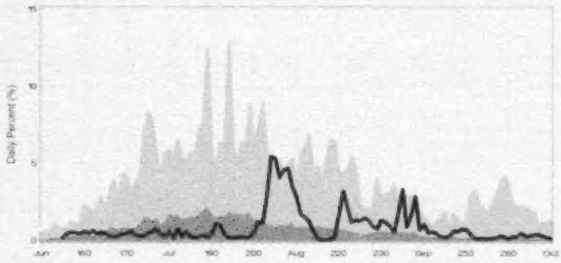

1992 Robertson Creek Station 1030230


1992 Sproat Water Temperature and Precipitation

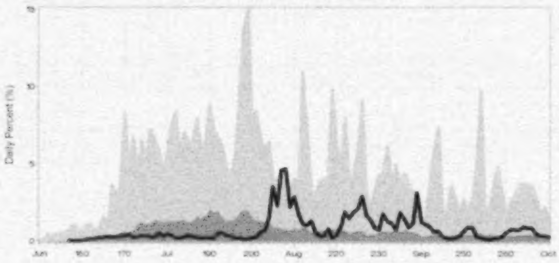

1992 Stamp Water Temperature and Precipitation


1992 Sproat Discharge

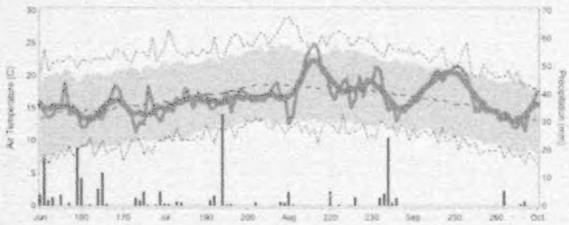

1992 Stamp Discharge



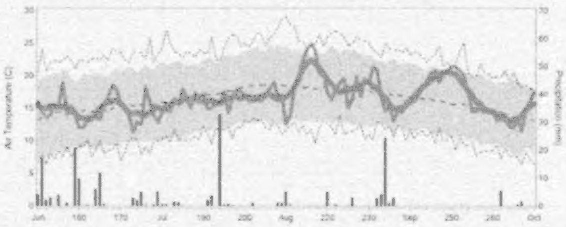
1993 Sproat Falls (Total Esc: 205,289)



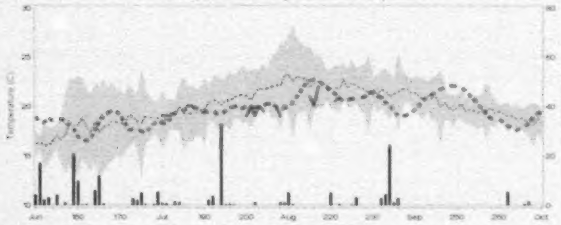
1993 Great Central Lake (Total Esc: 237,539)



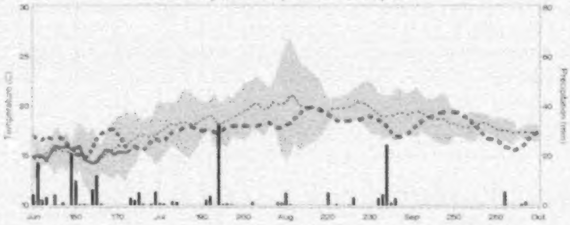
1993 Robertson Creek Station 1030230



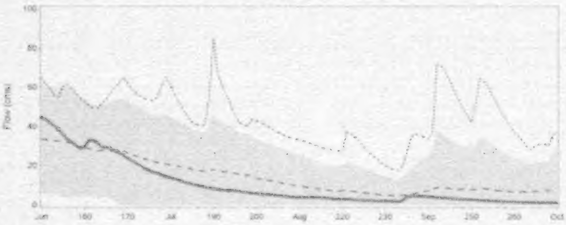
1993 Robertson Creek Station 1030230



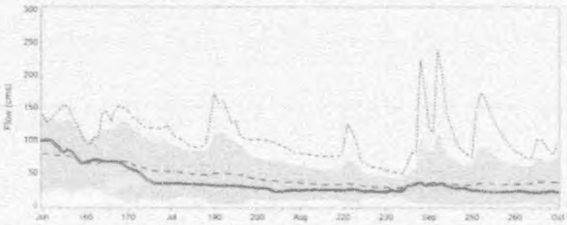
1993 Sproat Water Temperature and Precipitation



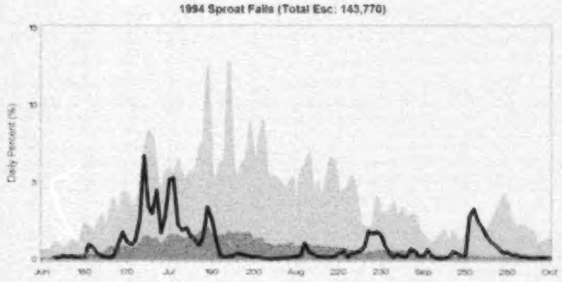
1993 Stamp Water Temperature and Precipitation



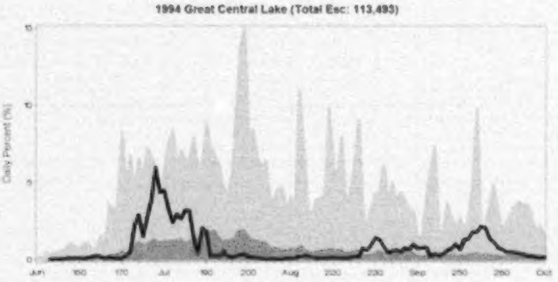
1993 Sproat Discharge



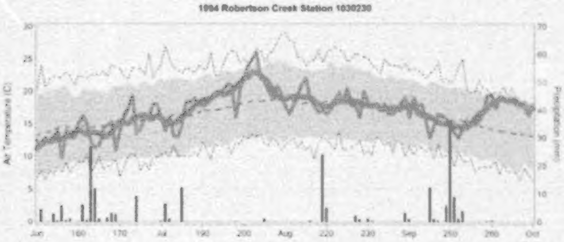
1993 Stamp Discharge



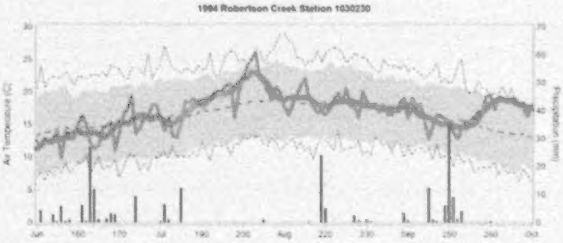
1994 Sproat Falls (Total Esc: 143,770)



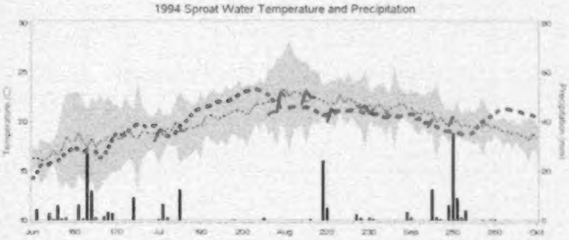
1994 Great Central Lake (Total Esc: 113,493)



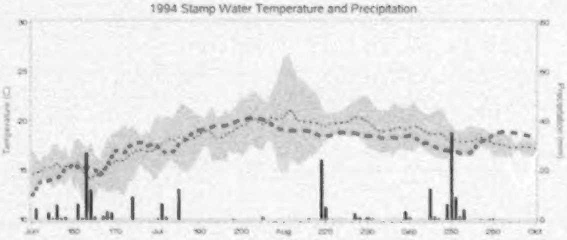
1994 Robertson Creek Station 1030230



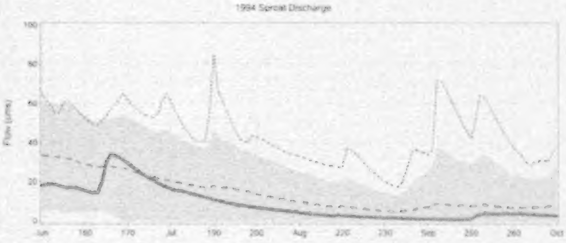
1994 Robertson Creek Station 1030230



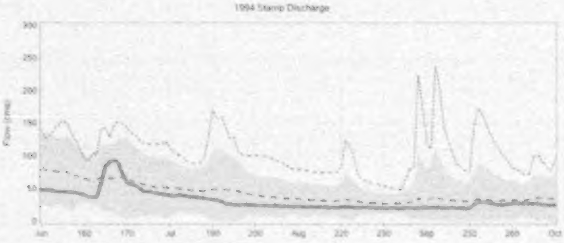
1994 Sproat Water Temperature and Precipitation



1994 Stamp Water Temperature and Precipitation

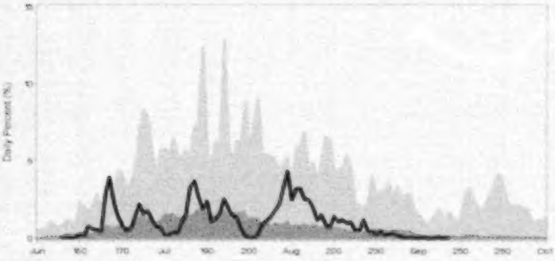


1994 Sproat Discharge

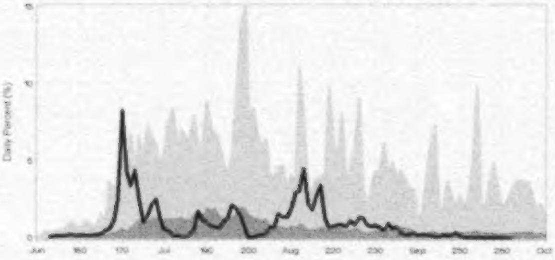


1994 Stamp Discharge

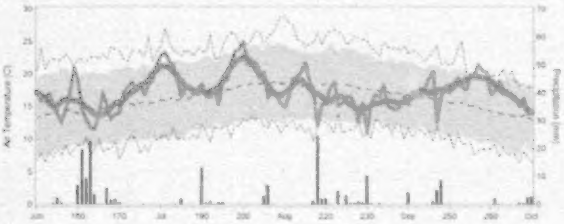
1995 Sproat Falls (Total Esc: 102,400)



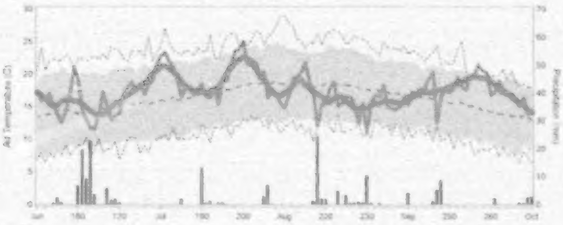
1995 Great Central Lake (Total Esc: 64,093)



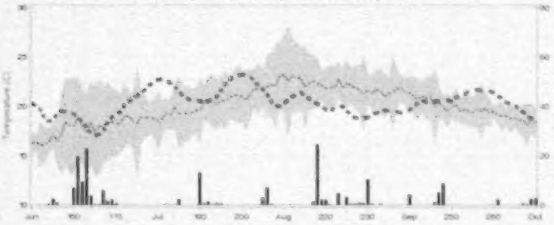
1995 Robertson Creek Station 1030230



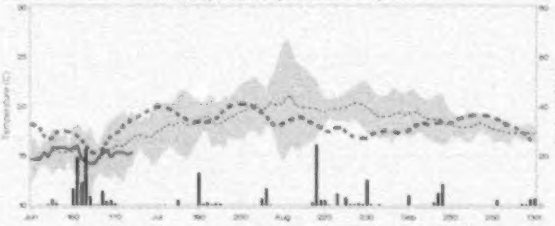
1995 Robertson Creek Station 1030230



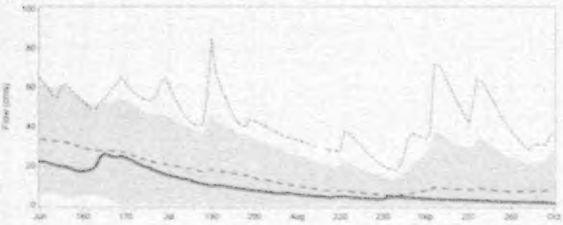
1995 Sproat Water Temperature and Precipitation



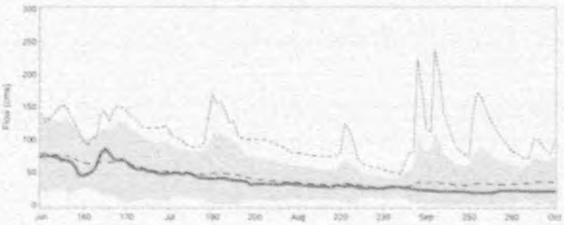
1995 Stamp Water Temperature and Precipitation



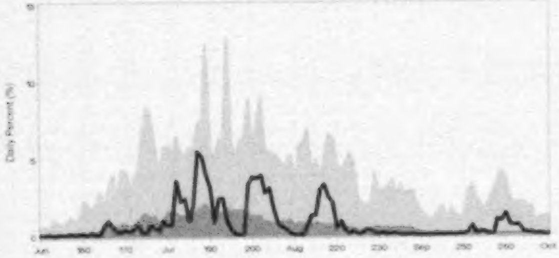
1995 Sproat Discharge



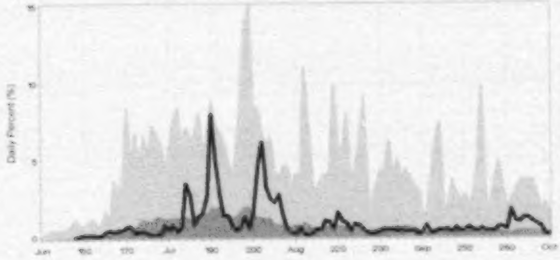
1995 Stamp Discharge



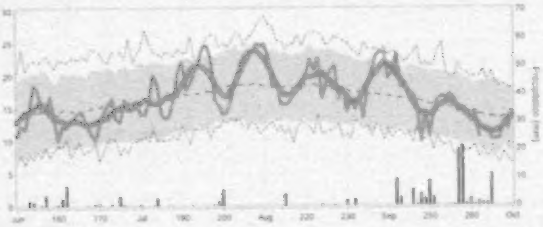
1996 Sproat Falls (Total Esc: 210,051)



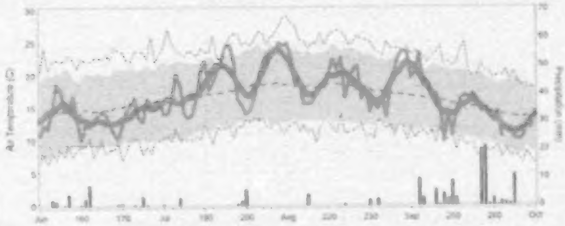
1996 Great Central Lake (Total Esc: 165,825)



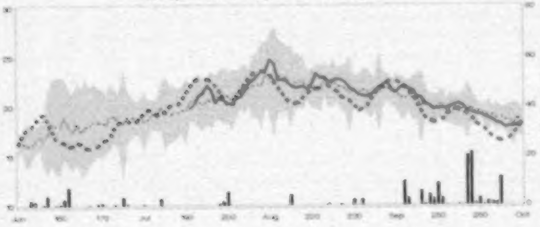
1996 Robertson Creek Station 1030230



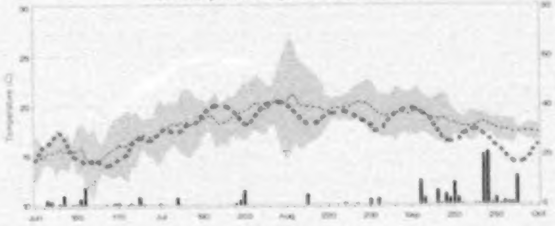
1996 Robertson Creek Station 1030230



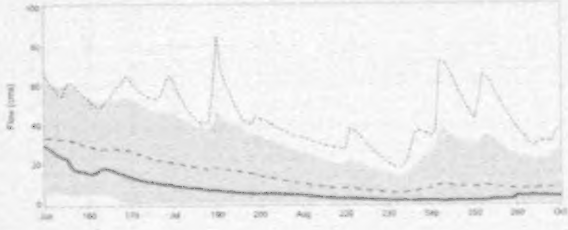
1996 Sproat Water Temperature and Precipitation



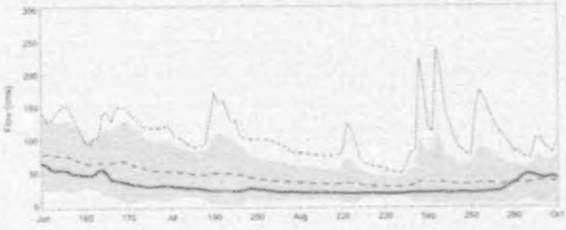
1996 Stamp Water Temperature and Precipitation

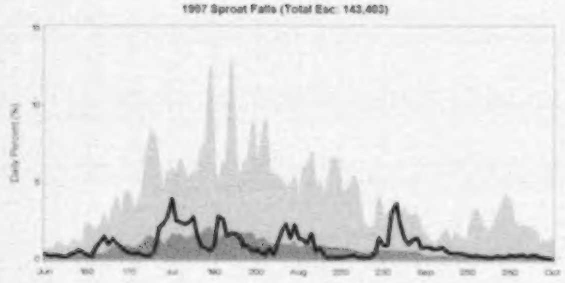


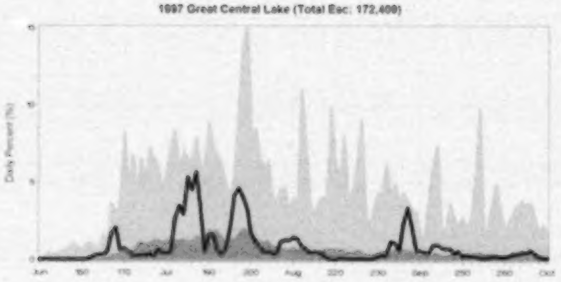
1996 Sproat Discharge

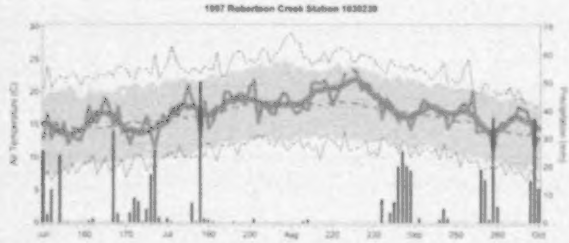


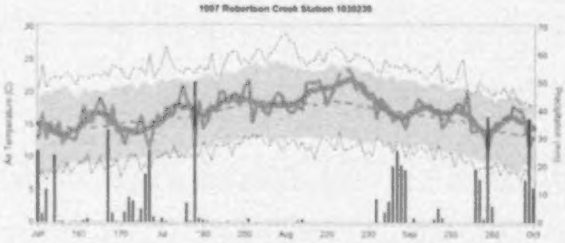
1996 Stamp Discharge

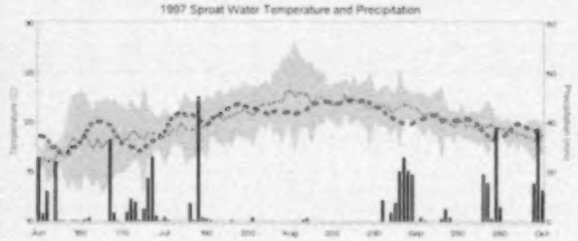


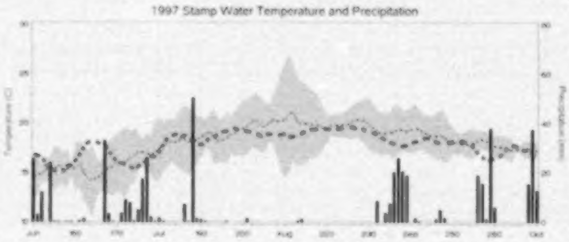

1997 Sproat Falls (Total Esc: 143,403)

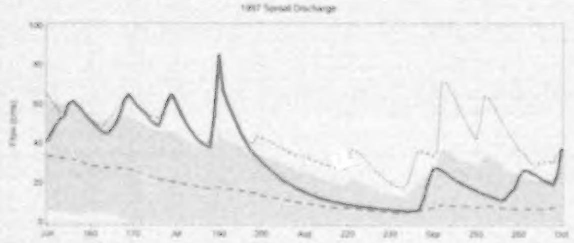

1997 Great Central Lake (Total Esc: 172,400)

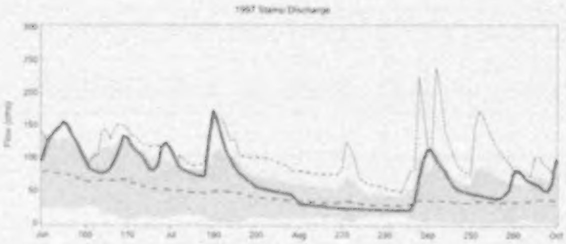

1997 Robertson Creek Station 1030230

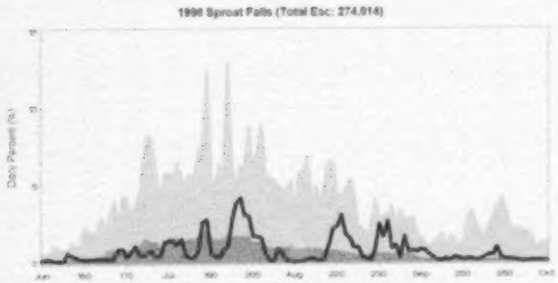

1997 Robertson Creek Station 1030230

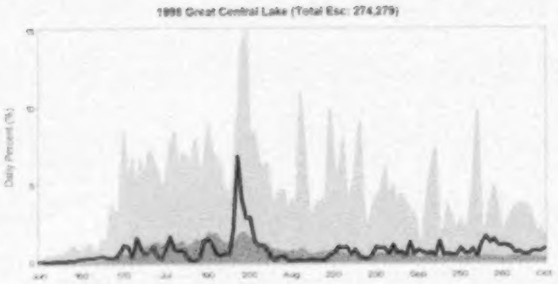

1997 Sproat Water Temperature and Precipitation

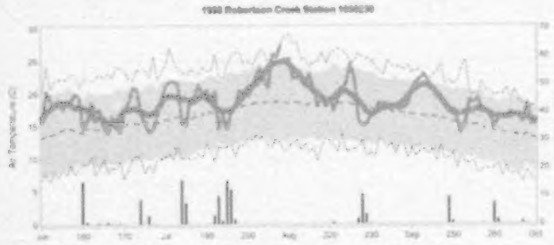

1997 Stamp Water Temperature and Precipitation

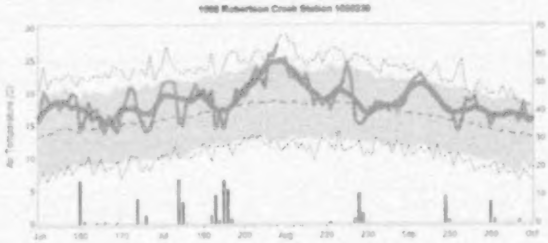

1997 Sproat Discharge

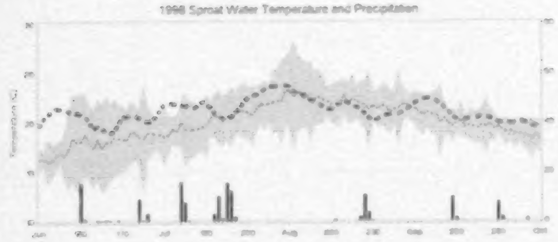

1997 Stamp Discharge

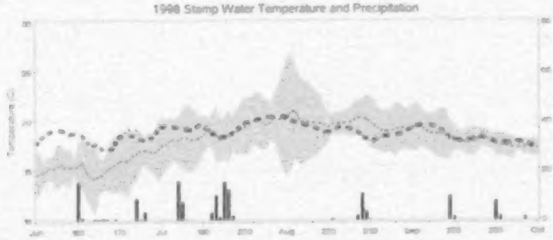

1998 Sproat Falls (Total Esc: 274,014)

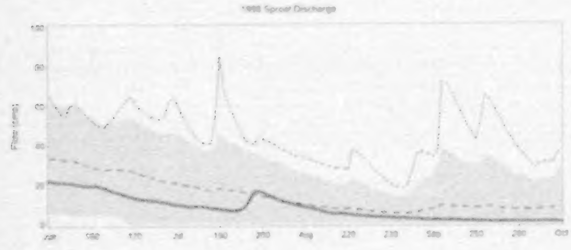

1998 Great Central Lake (Total Esc: 274,279)

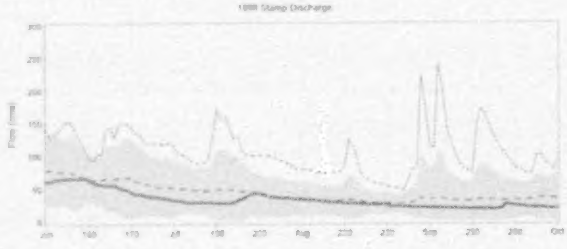

1998 Robertson Creek Station 1030230

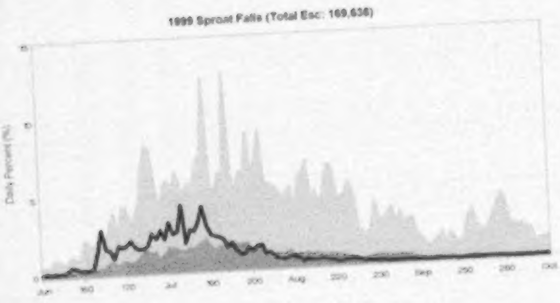

1998 Robertson Creek Station 1030230

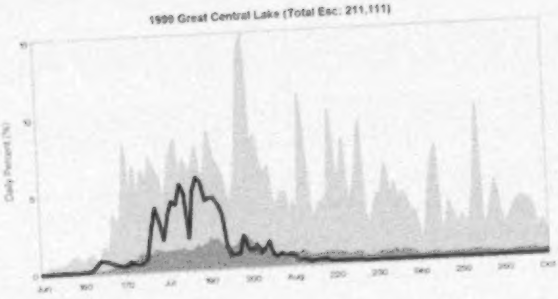

1998 Sproat Water Temperature and Precipitation

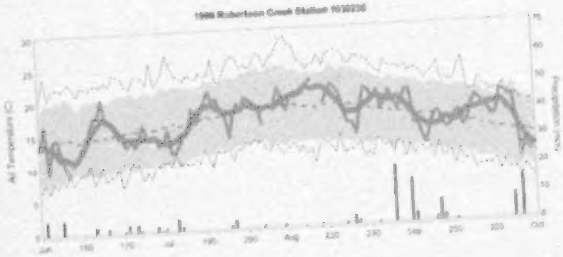

1998 Stamp Water Temperature and Precipitation

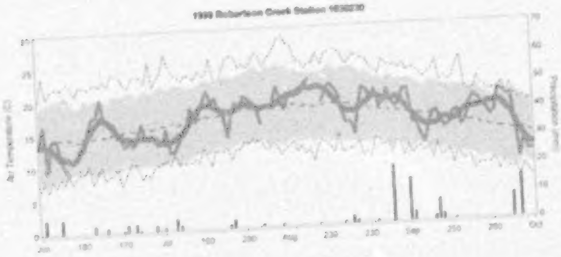

1998 Sproat Discharge

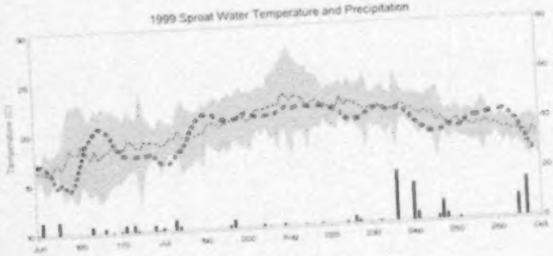

1998 Stamp Discharge

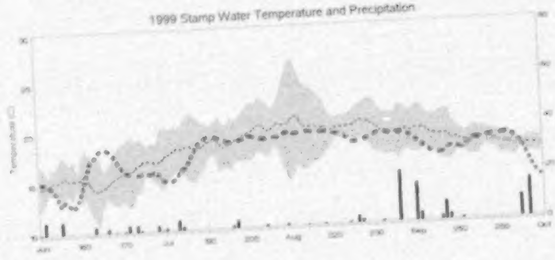

1999 Sproat Falls (Total Esc: 169,638)

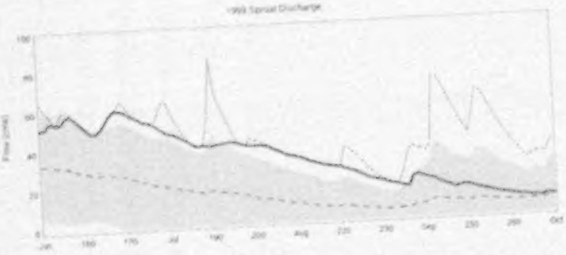

1999 Great Central Lake (Total Esc: 211,111)

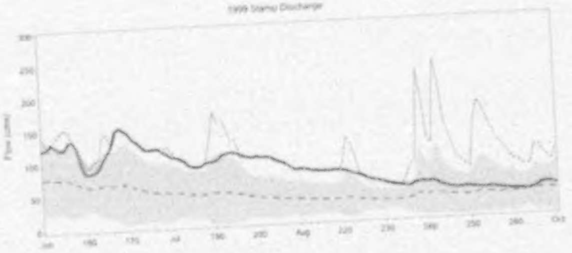

1999 Robertson Creek Station 1030230

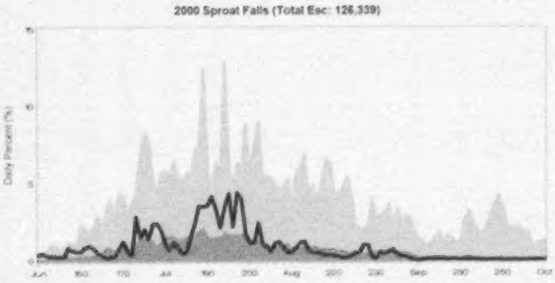

1999 Robertson Creek Station 1030230

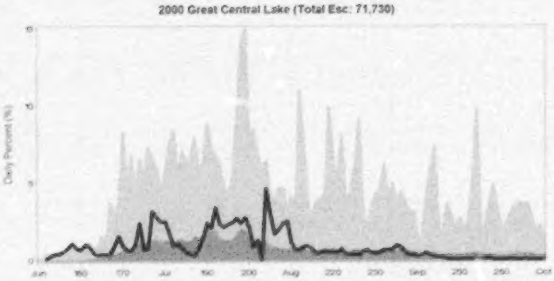

1999 Sproat Water Temperature and Precipitation

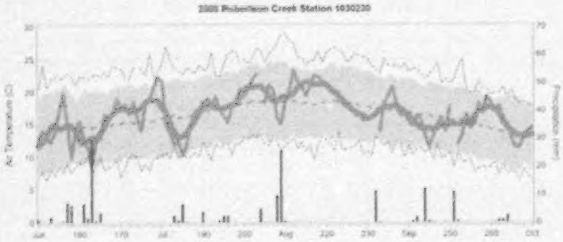

1999 Stamp Water Temperature and Precipitation

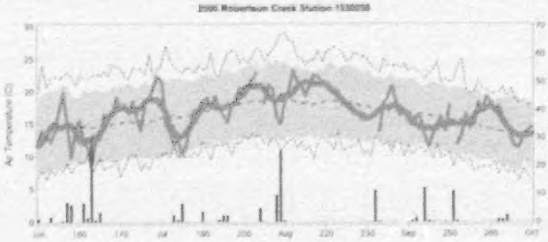

1999 Sproat Discharge

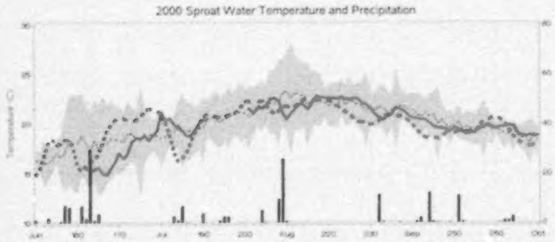

1999 Stamp Discharge

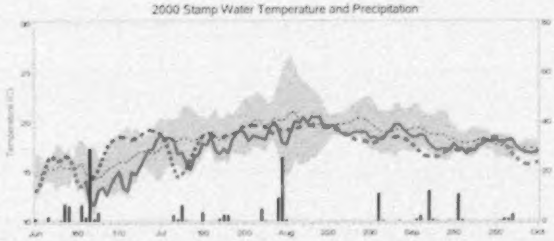

2000 Sproat Falls (Total Esc: 126,339)

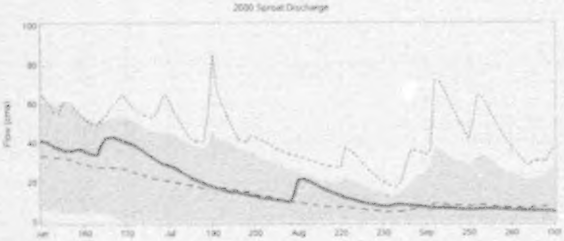

2000 Great Central Lake (Total Esc: 71,730)

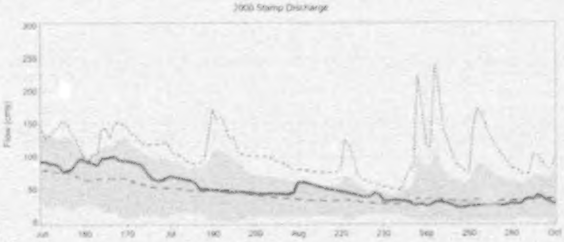

2000 Robertson Creek Station 1030230

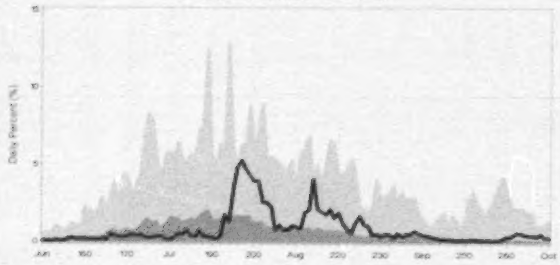

2000 Robertson Creek Station 1030230


2000 Sproat Water Temperature and Precipitation

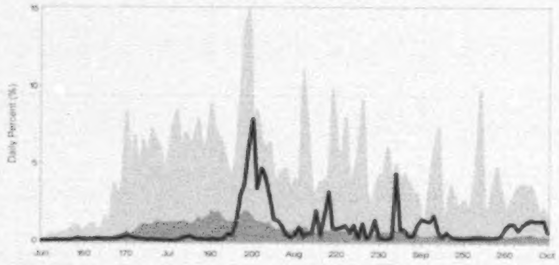

2000 Stamp Water Temperature and Precipitation


2000 Sproat Discharge

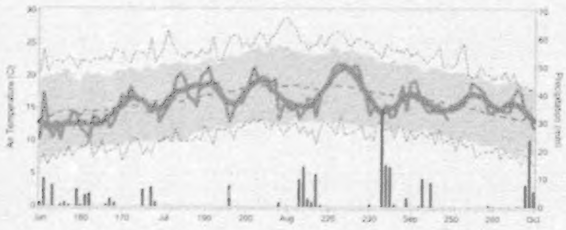

2000 Stamp Discharge



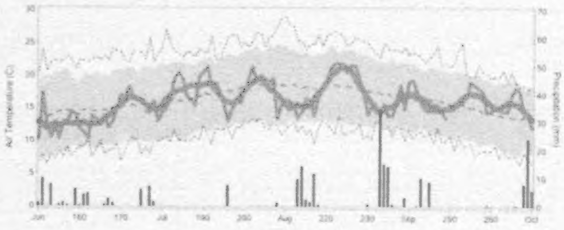
2001 Sproat Falls (Total Esc: 371,518)



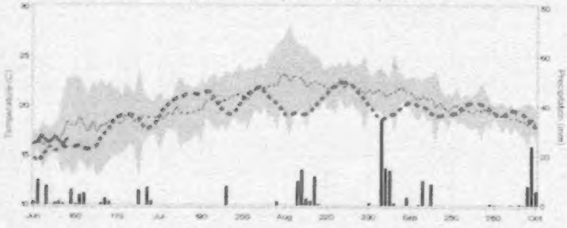
2001 Great Central Lake (Total Esc: 406,510)



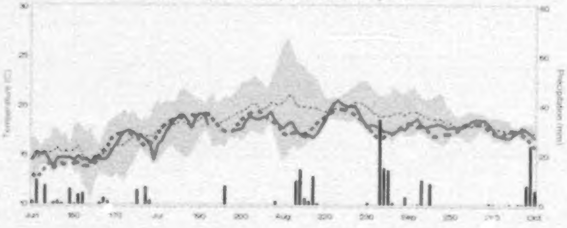
2001 Robertson Creek Station 1030230



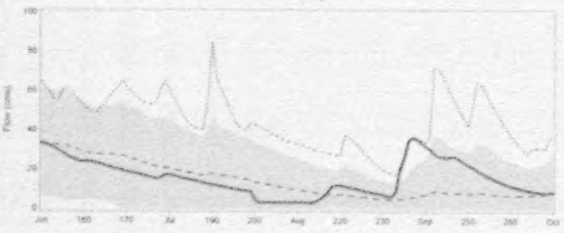
2001 Robertson Creek Station 1030230



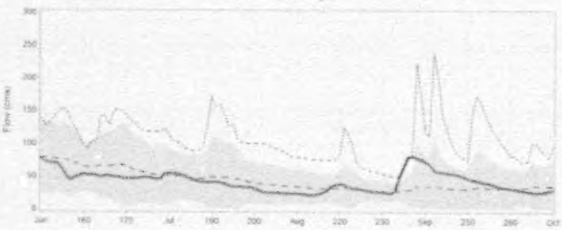
2001 Sproat Water Temperature and Precipitation



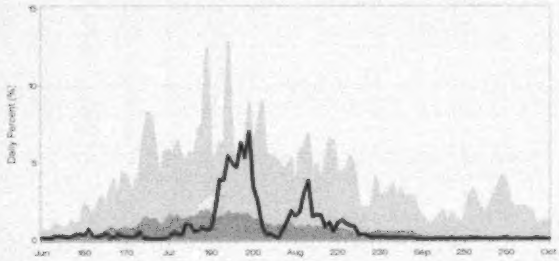
2001 Stamp Water Temperature and Precipitation

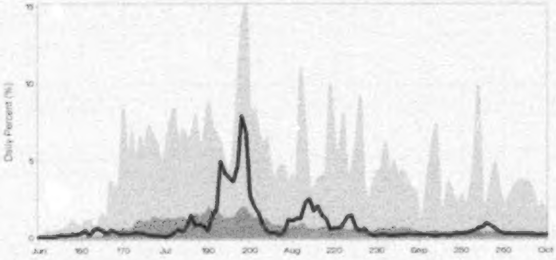


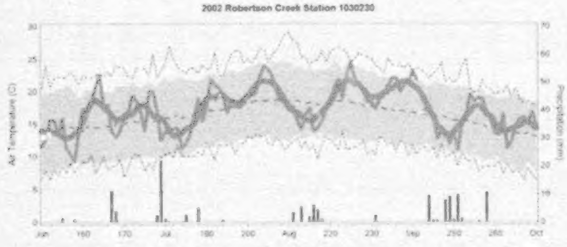
2001 Sproat Discharge

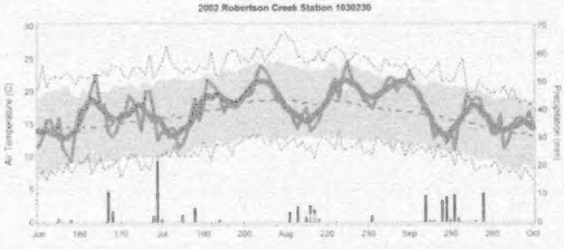


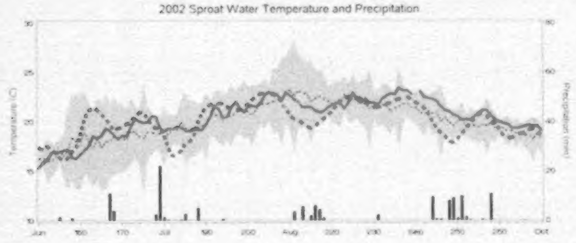
2001 Stamp Discharge

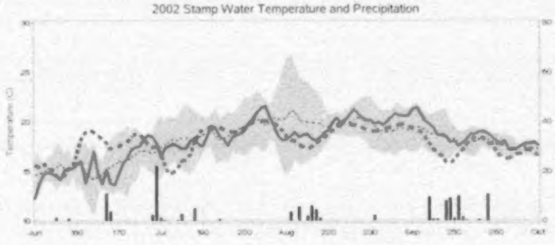

2002 Sproat Falls (Total Esc: 220,189)

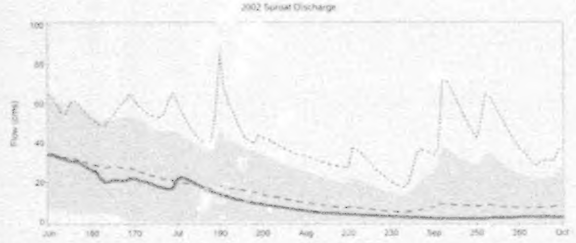

2002 Great Central Lake (Total Esc: 281,336)

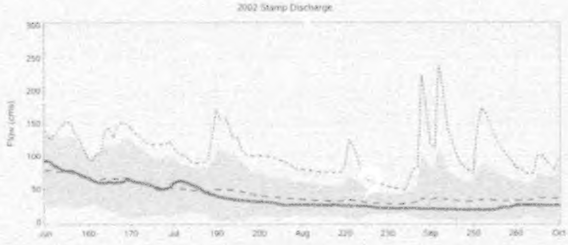

2002 Robertson Creek Station 1030230


2002 Robertson Creek Station 1030230

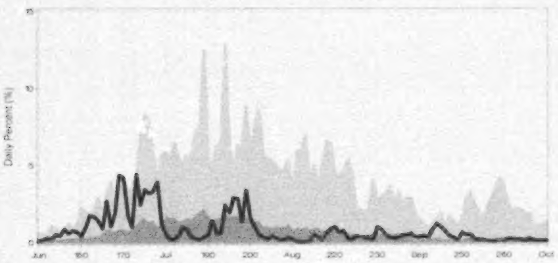

2002 Sproat Water Temperature and Precipitation


2002 Stamp Water Temperature and Precipitation

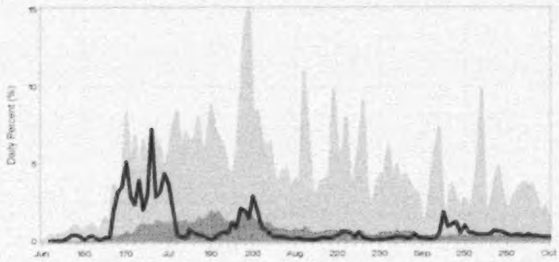

2002 Sproat Discharge


2002 Stamp Discharge

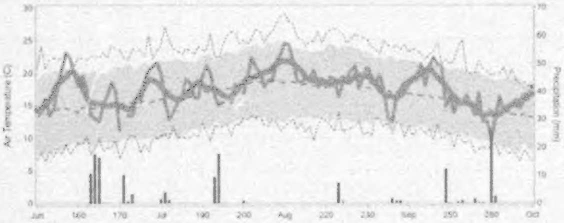
2003 Sproat Falls (Total Esc: 189,001)



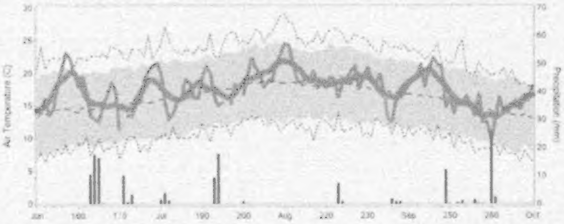
2003 Great Central Lake (Total Esc: 241,755)



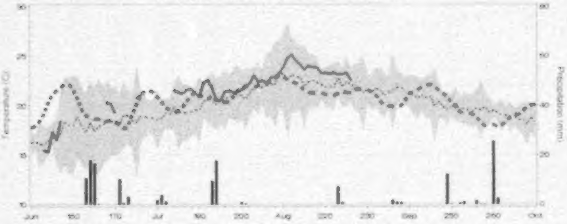
2003 Robertson Creek Station 1030230



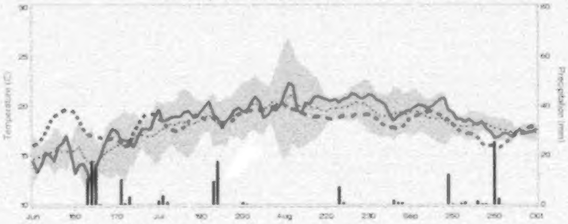
2003 Robertson Creek Station 1030230



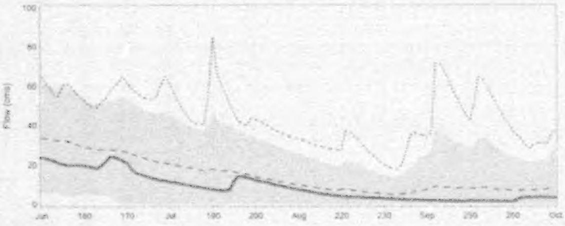
2003 Sproat Water Temperature and Precipitation



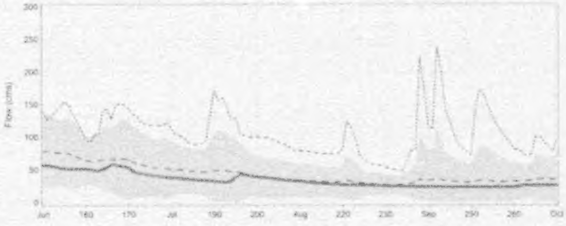
2003 Stamp Water Temperature and Precipitation



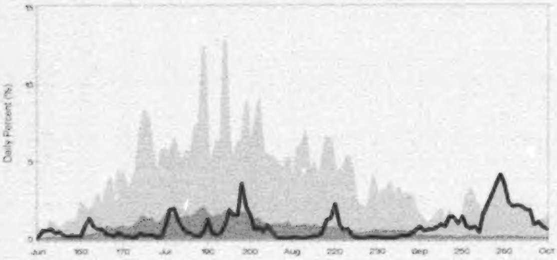
2003 Sproat Discharge



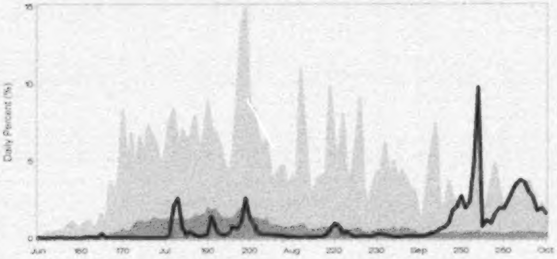
2003 Stamp Discharge



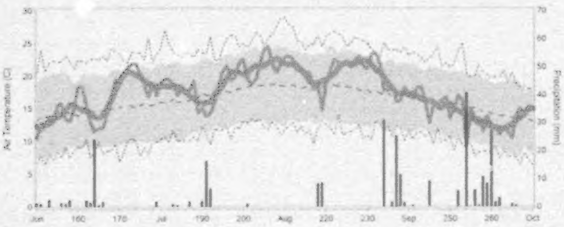
2004 Sproat Falls (Total Esc: 149,947)



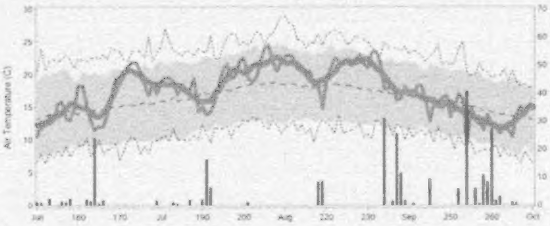
2004 Great Central Lake (Total Esc: 206,618)



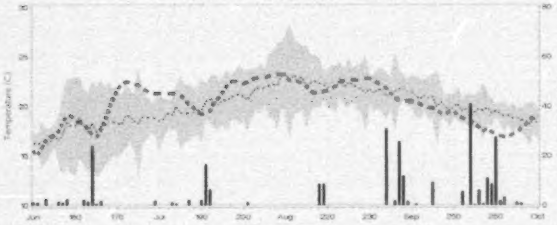
2004 Robertson Creek Station 1030230



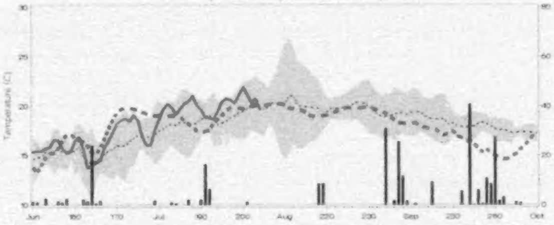
2004 Robertson Creek Station 1030230



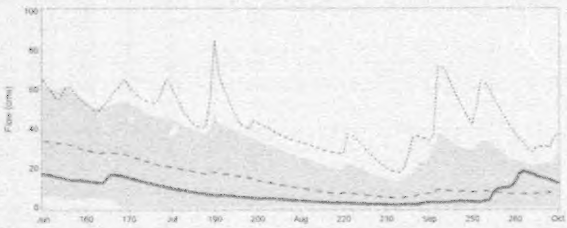
2004 Sproat Water Temperature and Precipitation



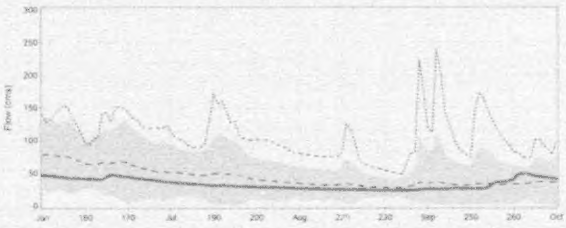
2004 Stamp Water Temperature and Precipitation

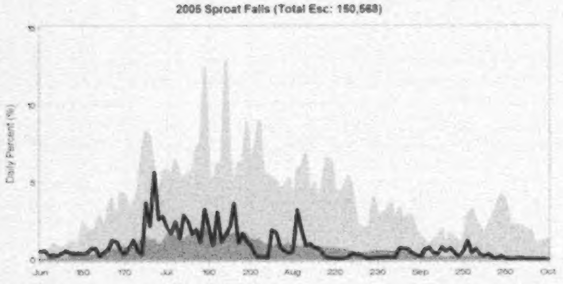


2004 Sproat Discharge

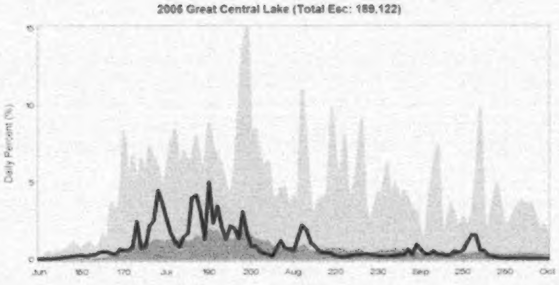


2004 Stamp Discharge

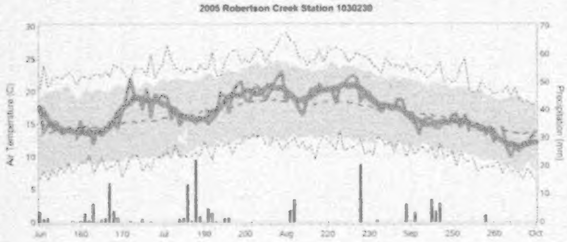




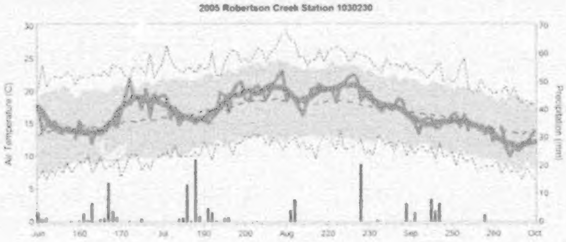
2005 Sproat Falls (Total Esc: 150,568)



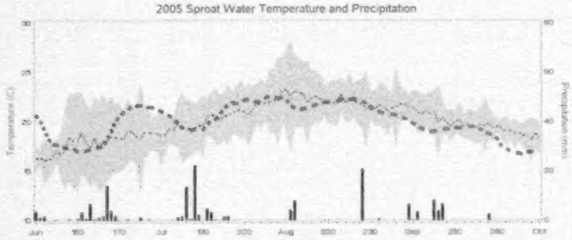
2005 Great Central Lake (Total Esc: 189,122)



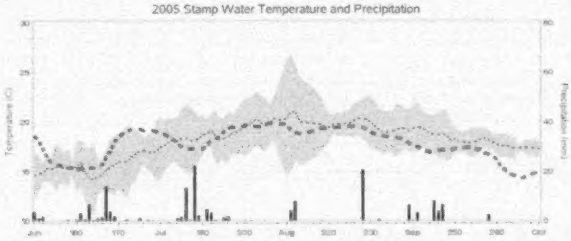
2005 Robertson Creek Station 1030230



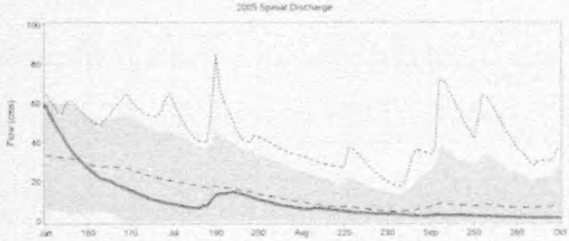
2005 Robertson Creek Station 1030230



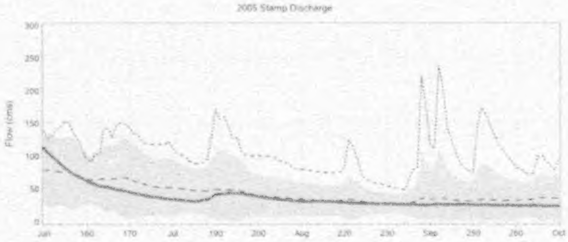
2005 Sproat Water Temperature and Precipitation



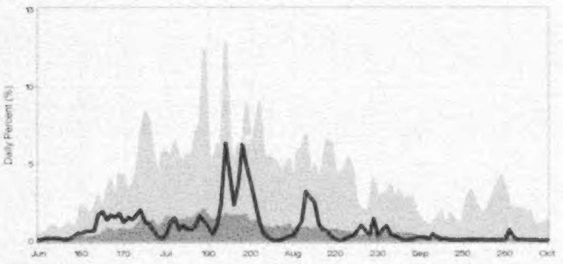
2005 Stamp Water Temperature and Precipitation

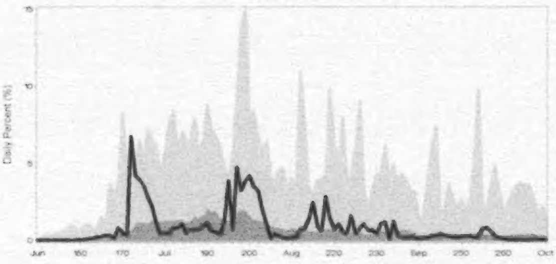


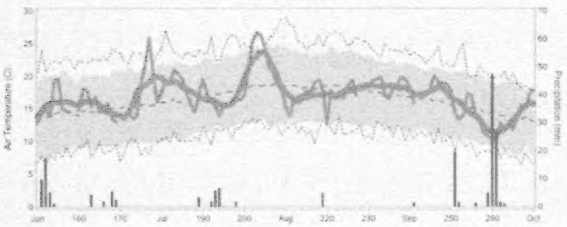
2005 Sproat Discharge

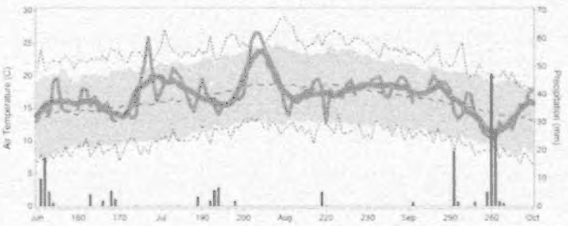


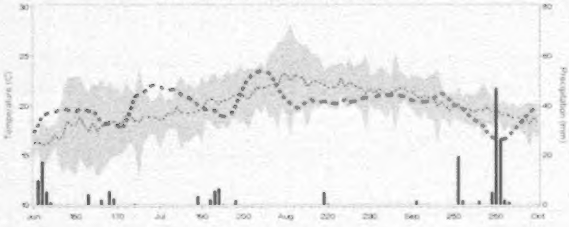
2005 Stamp Discharge

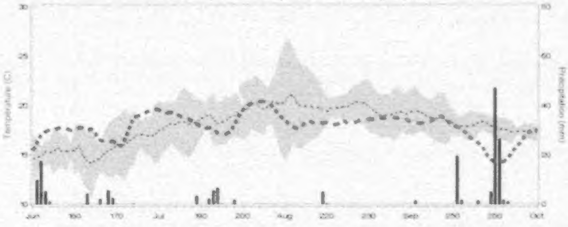

2006 Sproat Falls (Total Esc: 63,357)

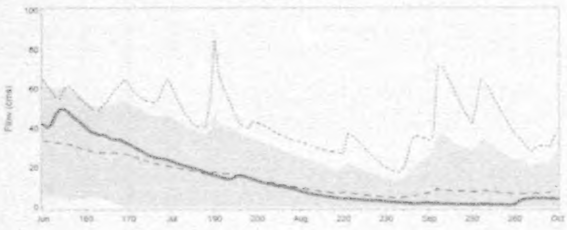

2006 Great Central Lake (Total Esc: 131,568)

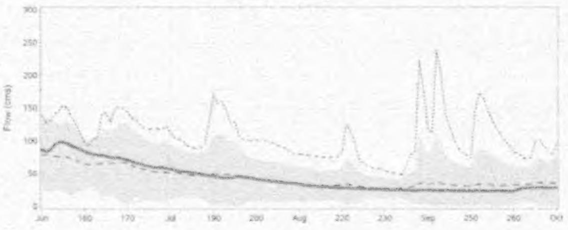

2006 Robertson Creek Station 1030230

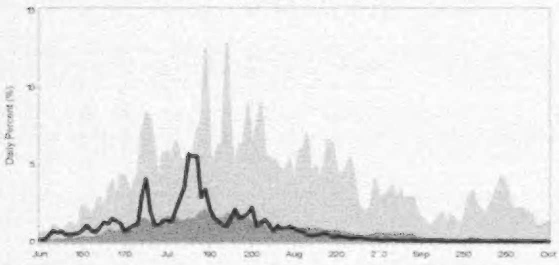

2006 Robertson Creek Station 1030230

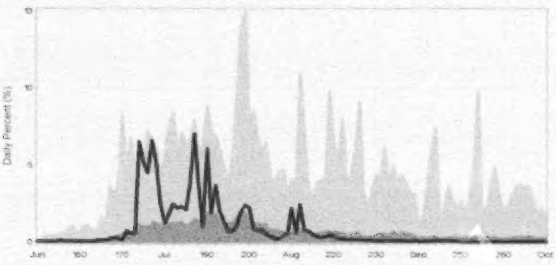

2006 Sproat Water Temperature and Precipitation

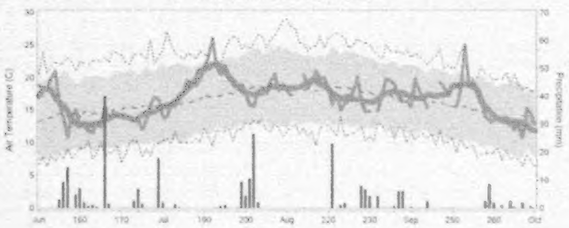

2006 Stamp Water Temperature and Precipitation

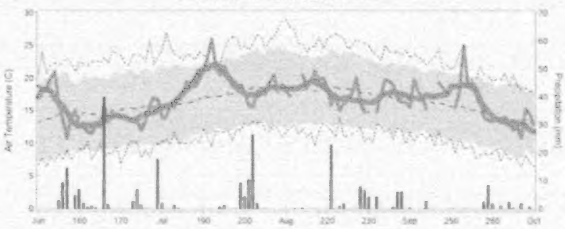

2006 Sproat Discharge

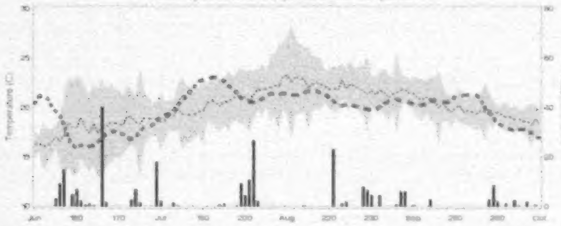

2006 Stamp Discharge

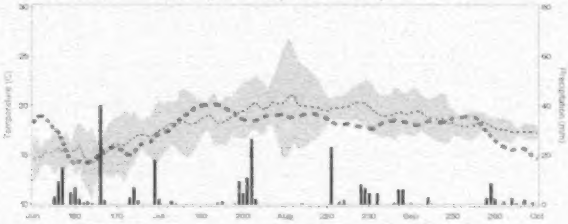

2007 Sproat Falls (Total Esc: 71,975)

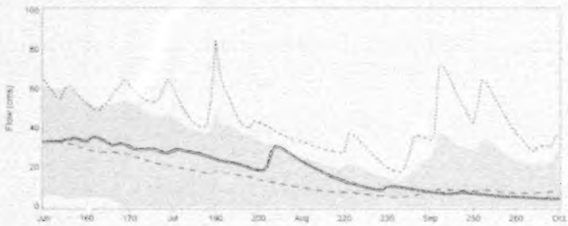

2007 Great Central Lake (Total Esc: 76,373)

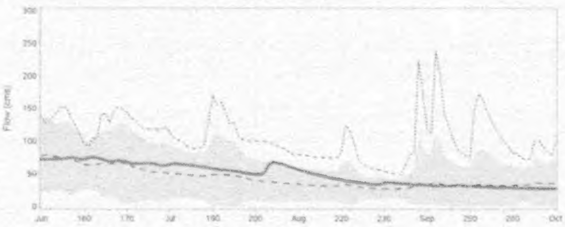

2007 Robertson Creek Station 1030230

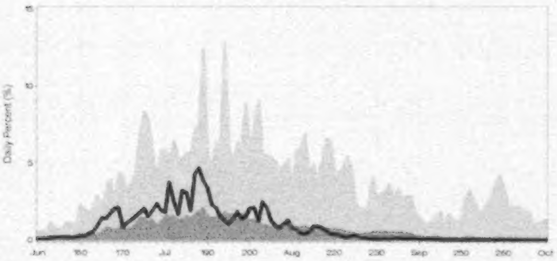

2007 Robertson Creek Station 1030230

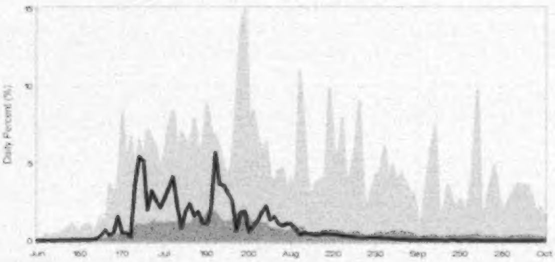

2007 Sproat Water Temperature and Precipitation

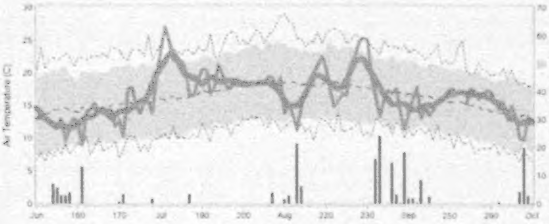

2007 Stamp Water Temperature and Precipitation

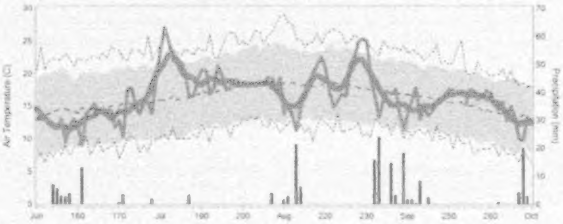

2007 Sproat Discharge

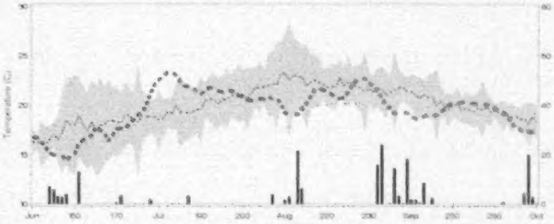

2007 Stamp Discharge

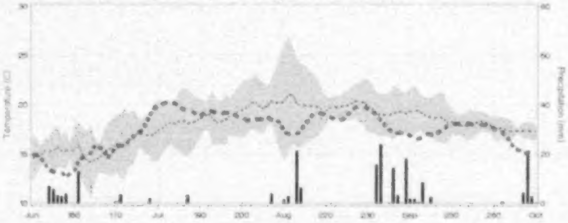

2008 Sproat Falls (Total Esc: 116,844)

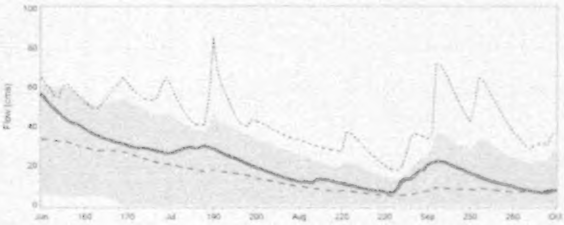

2008 Great Central Lake (Total Esc: 74,024)

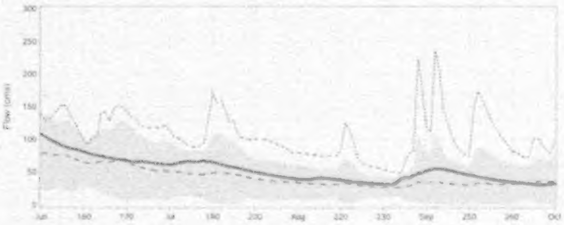

2008 Robertson Creek Station 1030230

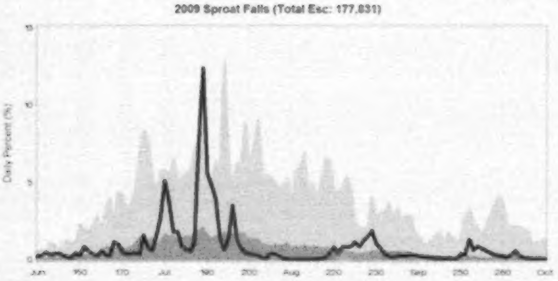

2008 Robertson Creek Station 1030230

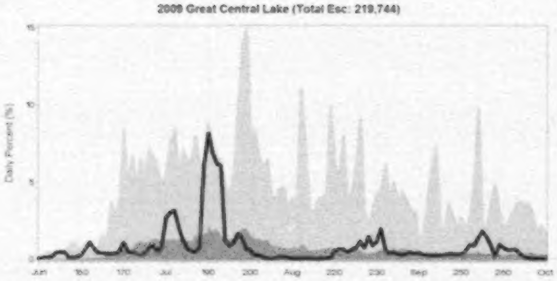

2008 Sproat Water Temperature and Precipitation

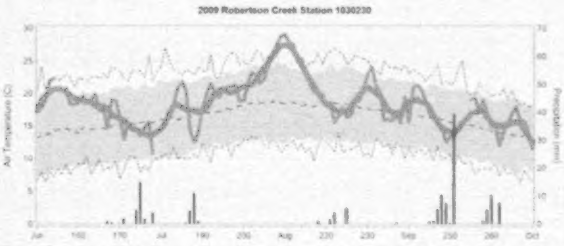

2008 Stamp Water Temperature and Precipitation

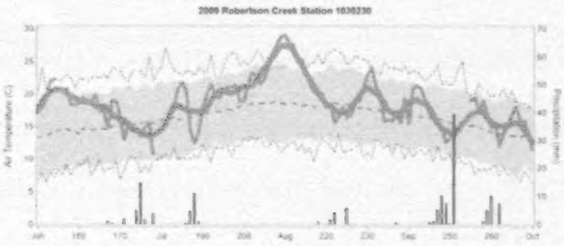

2008 Sproat Discharge

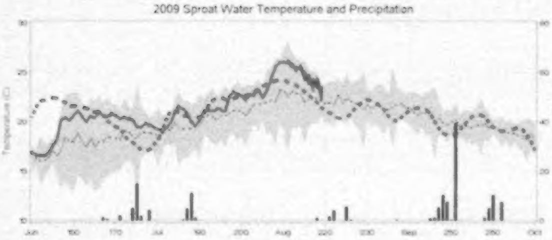

2008 Stamp Discharge

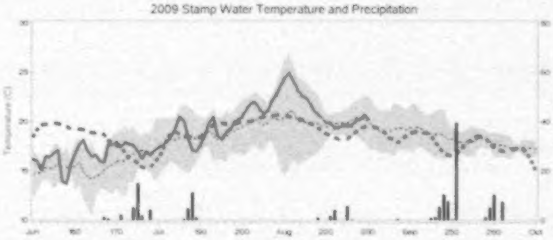

2009 Sproat Falls (Total Esc: 177,831)

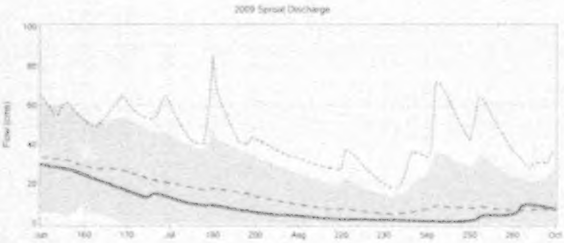

2009 Great Central Lake (Total Esc: 219,744)

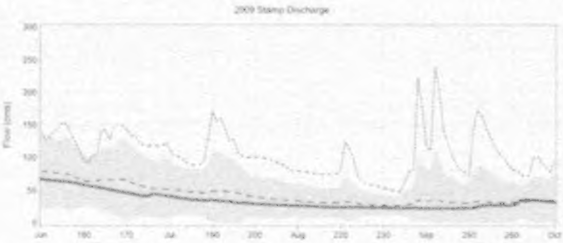

2009 Robertson Creek Station 1030230

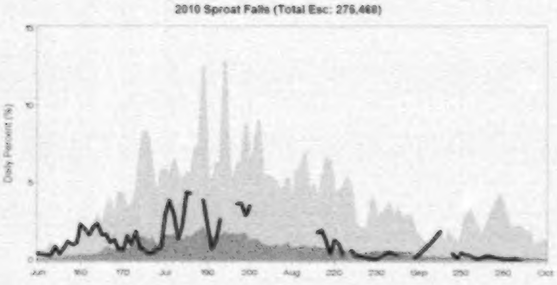

2009 Robertson Creek Station 1030230

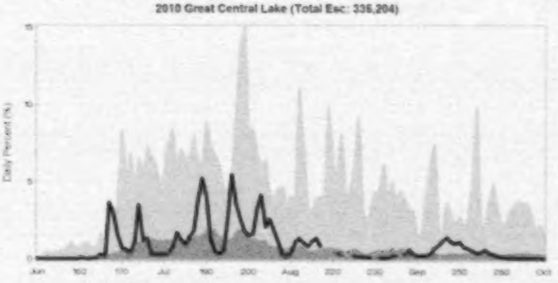

2009 Sproat Water Temperature and Precipitation

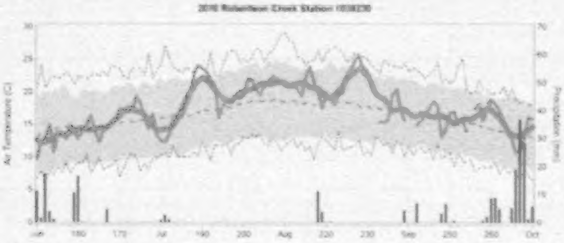

2009 Stamp Water Temperature and Precipitation

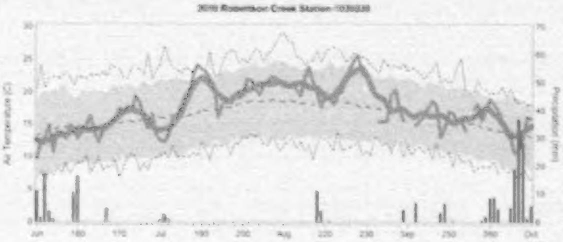

2009 Sproat Discharge

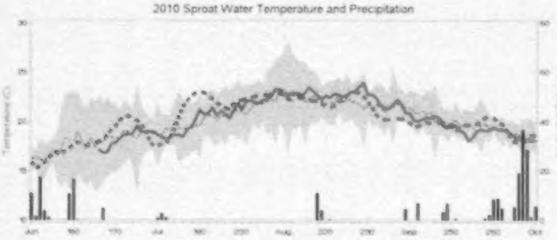

2009 Stamp Discharge

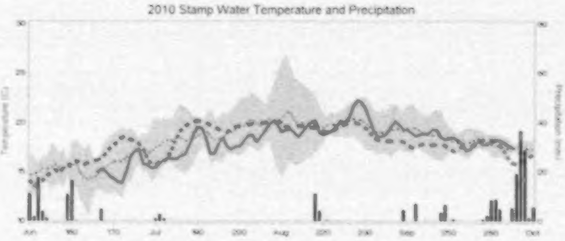

2010 Sproat Falls (Total Esc: 276,468)

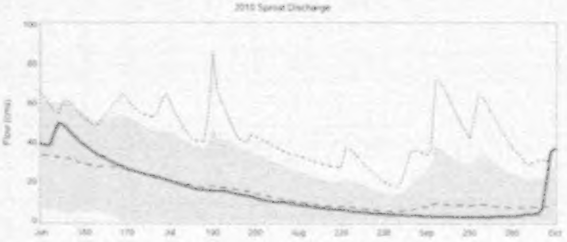

2010 Great Central Lake (Total Esc: 336,204)

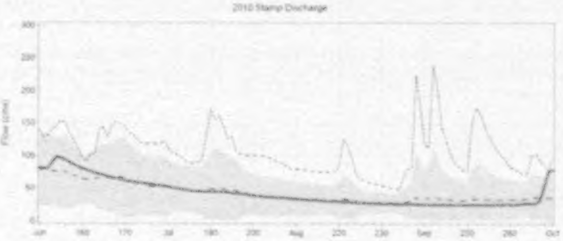

2010 Robertson Creek Station 1038230


2010 Robertson Creek Station 1038230

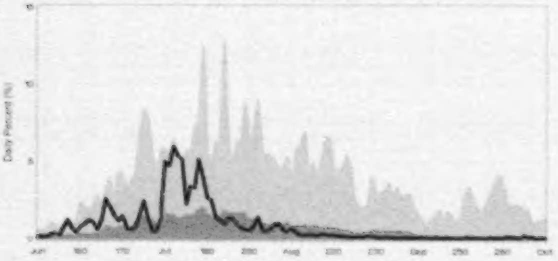

2010 Sproat Water Temperature and Precipitation


2010 Stamp Water Temperature and Precipitation

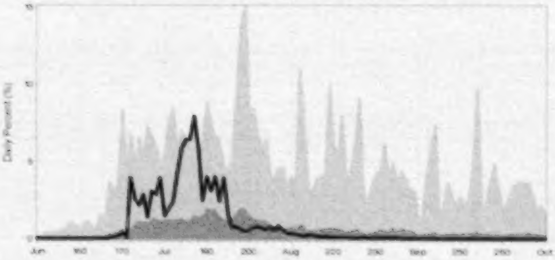

2010 Sproat Discharge


2010 Stamp Discharge

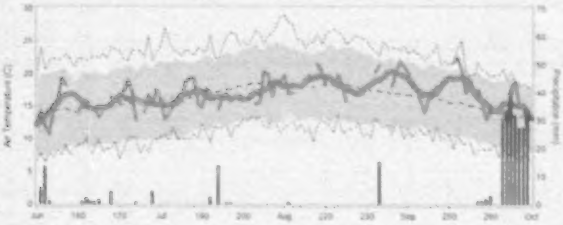
2011 Sproat Falls (Total Esc: 439,214)



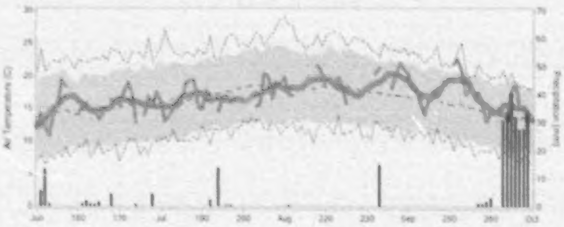
2011 Great Central Lake (Total Esc: 446,438)



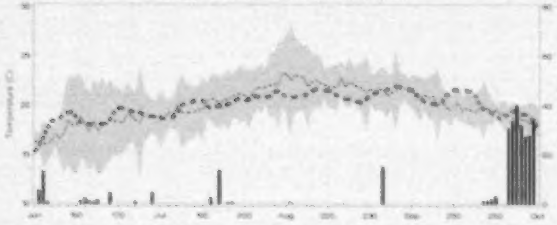
2011 Robertson Creek Station [illegible]



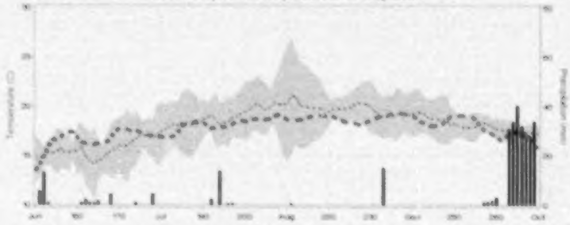
2011 Robertson Creek Station [illegible]



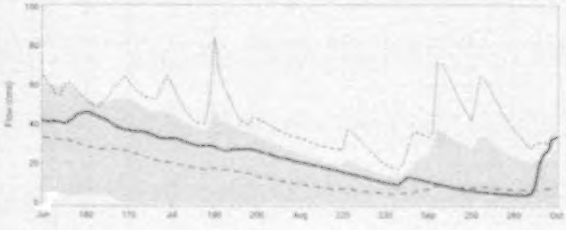
2011 Sproat Water Temperature and Precipitation



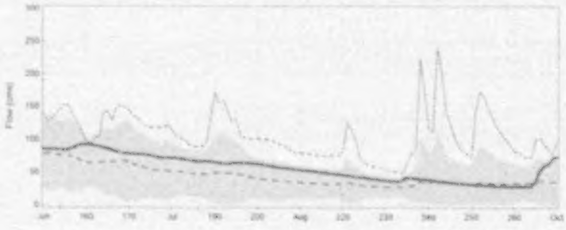
2011 Stamp Water Temperature and Precipitation

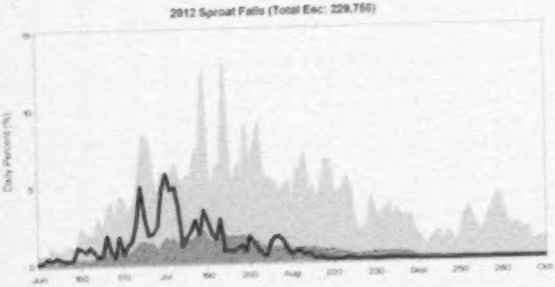


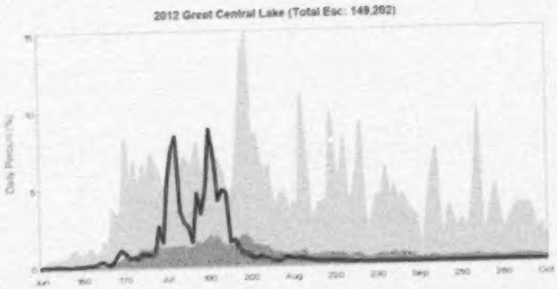
2011 Sproat Discharge

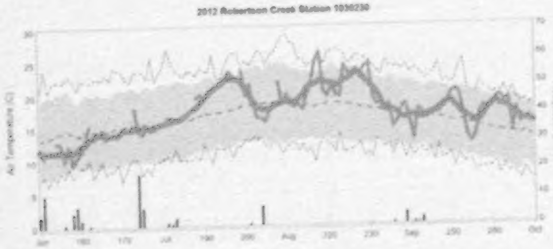


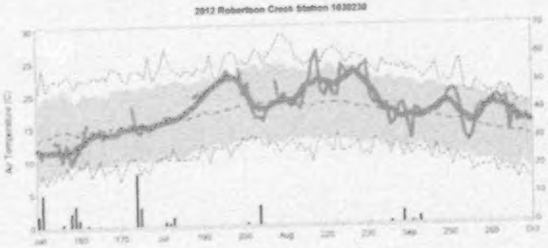
2011 Stamp Discharge

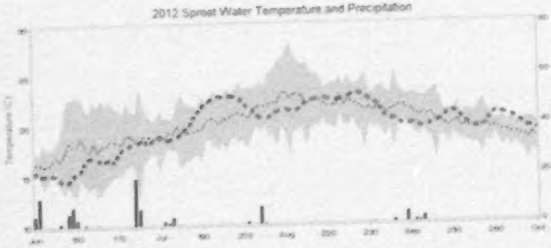


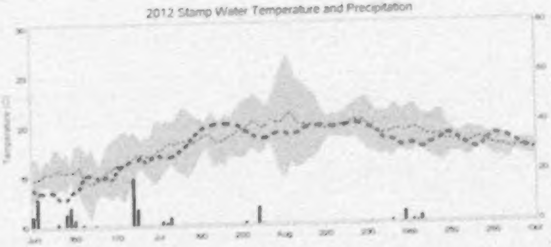

2012 Sproat Falls (Total Esc: 229,756)
Daily Percent (%)
0
5
10
15
Jun
160
170
Jul
190
200
Aug
220
230
Sep
250
260
Oct

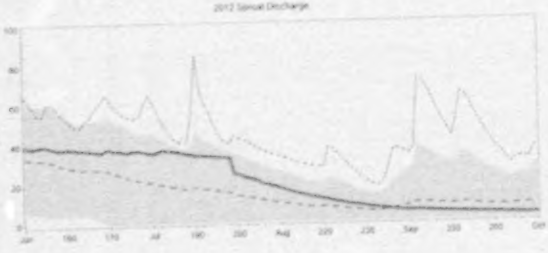

2012 Great Central Lake (Total Esc: 149,202)
Daily Percent (%)
0
5
10
15
Jun
160
170
Jul
190
200
Aug
220
230
Sep
250
260
Oct

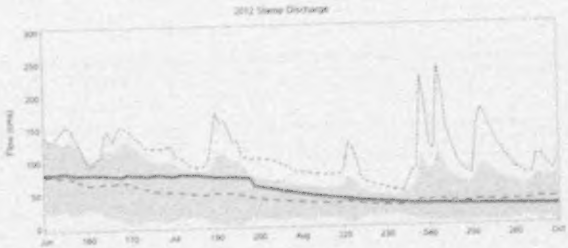

2012 Robertson Creek Station 1030230
Air Temperature (C)
Precipitation (mm)
0
5
10
15
20
25
30
10
20
30
40
50
60
70
Jun
160
170
Jul
190
200
Aug
220
230
Sep
250
260
Oct


2012 Robertson Creek Station 1030230
Air Temperature (C)
Precipitation (mm)
0
5
10
15
20
25
30
10
20
30
40
50
60
70
Jun
160
170
Jul
190
200
Aug
220
230
Sep
250
260
Oct

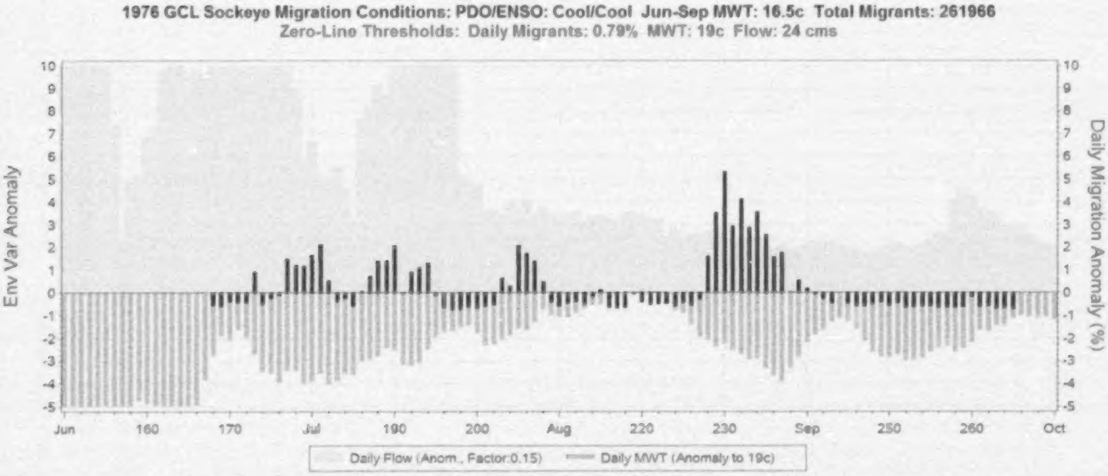

2012 Sproat Water Temperature and Precipitation
Temperature (C)
Precipitation (mm)
10
15
20
25
30
20
40
60
80
Jun
160
170
Jul
190
200
Aug
220
230
Sep
250
260
Oct

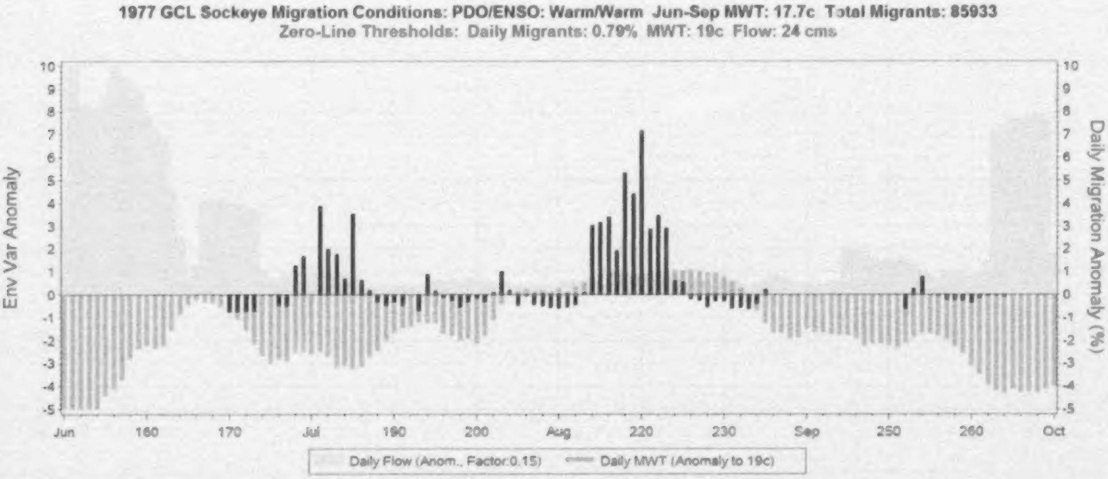

2012 Stamp Water Temperature and Precipitation
Temperature (C)
Precipitation (mm)
10
15
20
25
30
20
40
60
80
Jun
160
170
Jul
190
200
Aug
220
230
Sep
250
260
Oct


2012 Sproat Discharge
Flow (cms)
0
20
40
60
80
100
Jun
160
170
Jul
190
200
Aug
220
230
Sep
250
260
Oct

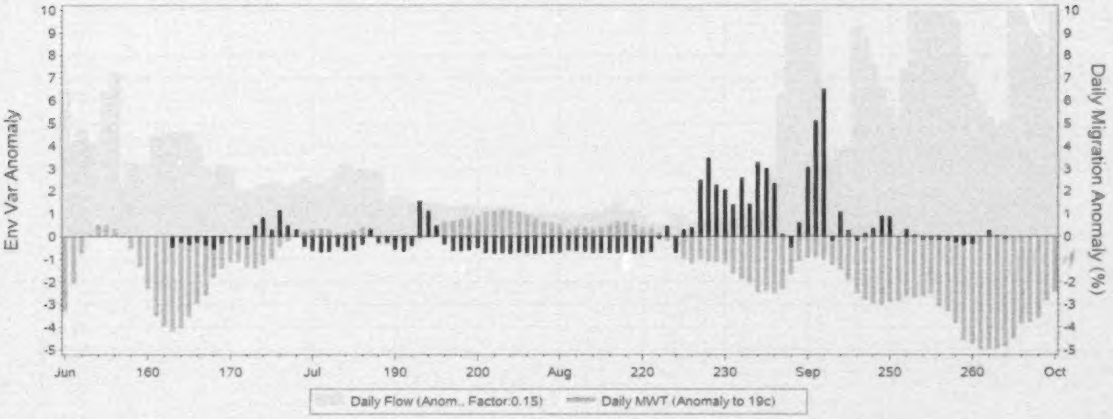

2012 Stamp Discharge
Flow (cms)
0
50
100
150
200
250
300
Jun
160
170
Jul
190
200
Aug
220
230
Sep
250
260
Oct

Appendix B. Annual anomaly plots for Great Central Lake sockeye migration, water temperature, and river discharge. Zero-line thresholds: (a) Daily migration rate = 0.79% (75th percentile of non-zero daily migration rates (1976-2012); (b) Water temperature = 19°C (at Stamp Falls); Discharge (at Stamp Falls) = 24 cms.

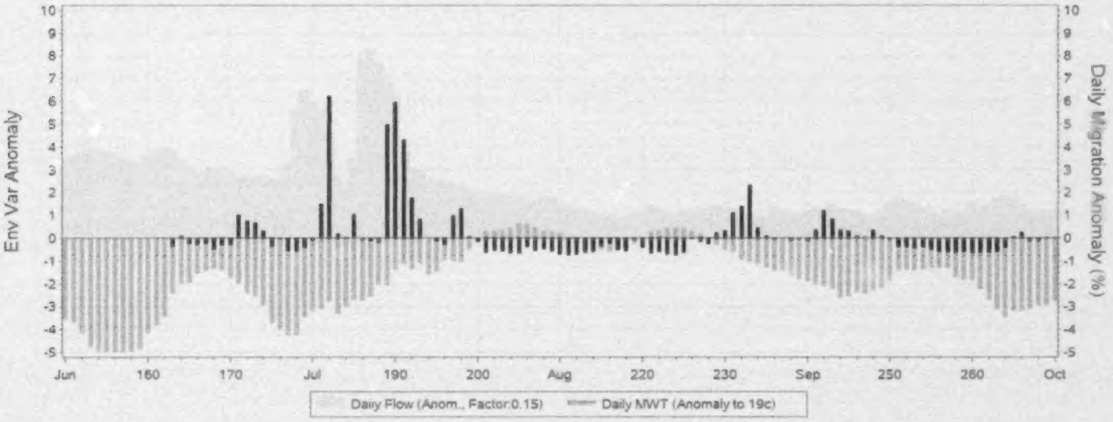

1976 GCL Sockeye Migration Conditions: PDO/ENSO: Cool/Cool Jun-Sep MWT: 16.5c Total Migrants: 261966
Zero-Line Thresholds: Daily Migrants: 0.79% MWT: 19c Flow: 24 cms


1977 GCL Sockeye Migration Conditions: PDO/ENSO: Warm/Warm Jun-Sep MWT: 17.7c Total Migrants: 85933
Zero-Line Thresholds: Daily Migrants: 0.79% MWT: 19c Flow: 24 cms

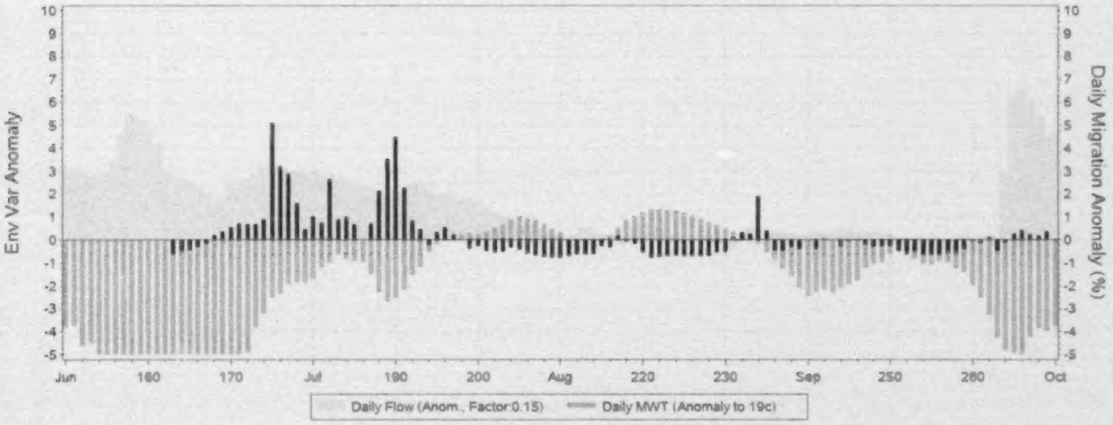
1978 GCL Sockeye Migration Conditions: PDO/ENSO: Warm/Warm Jun-Sep MWT: 18.3c Total Migrants: 120442
Zero-Line Thresholds: Daily Migrants: 0.79% MWT: 19c Flow: 24 cms



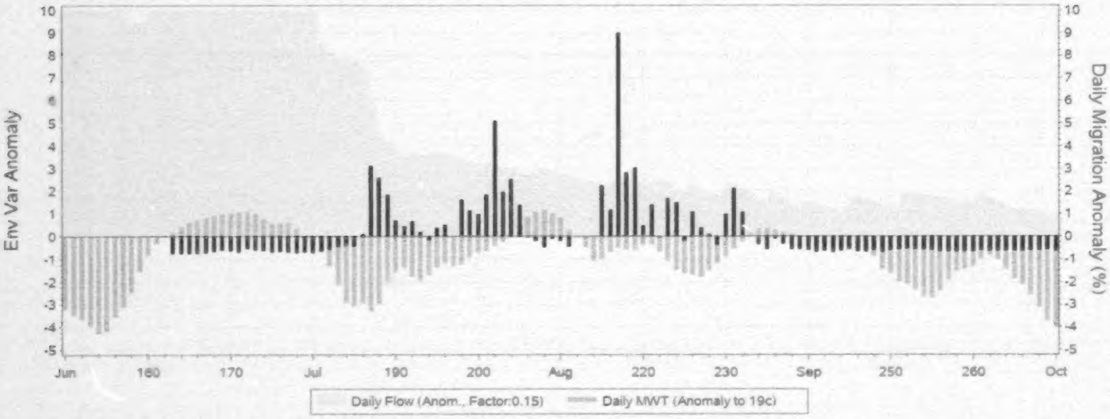
1980 GCL Sockeye Migration Conditions: PDO/ENSO: Warm/Warm Jun-Sep MWT: 17.5c Total Migrants: 165168
Zero-Line Thresholds: Daily Migrants: 0.79% MWT: 19c Flow: 24 cms



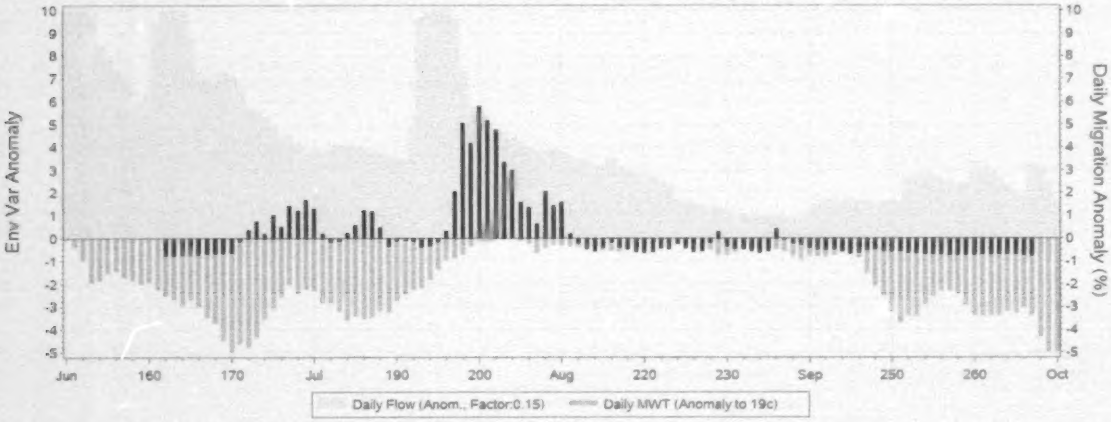
1981 GCL Sockeye Migration Conditions: PDO/ENSO: Warm/Neutral Jun-Sep MWT: 17.7c Total Migrants: 262791
Zero-Line Thresholds: Daily Migrants: 0.79% MWT: 19c Flow: 24 cms



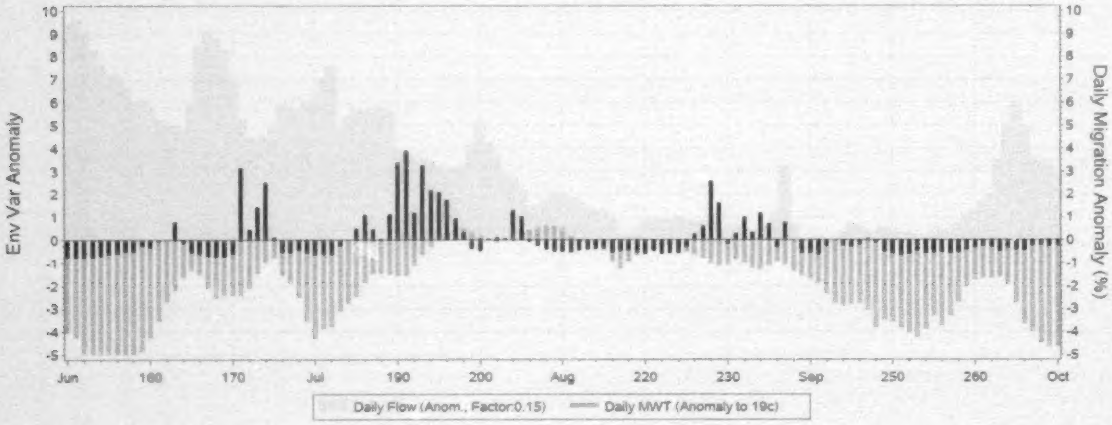
1982 GCL Sockeye Migration Conditions: PDO/ENSO: Warm/Neutral Jun-Sep MWT: 18.5c Total Migrants: 154058
Zero-Line Thresholds: Daily Migrants: 0.79% MWT: 19c Flow: 24 cms



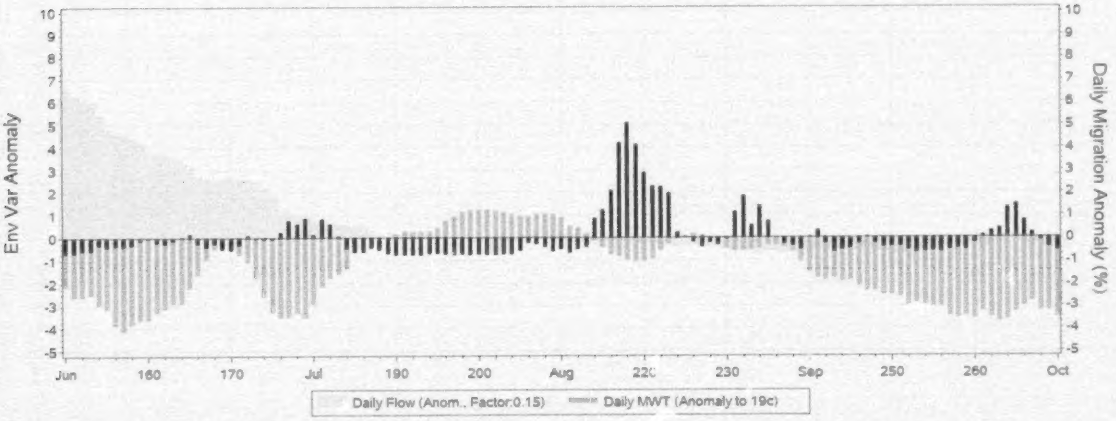
1983 GCL Sockeye Migration Conditions: PDO/ENSO: Warm/Warm Jun-Sep MWT: 17.8c Total Migrants: 377612
Zero-Line Thresholds: Daily Migrants: 0.79% MWT: 19c Flow: 24 cms



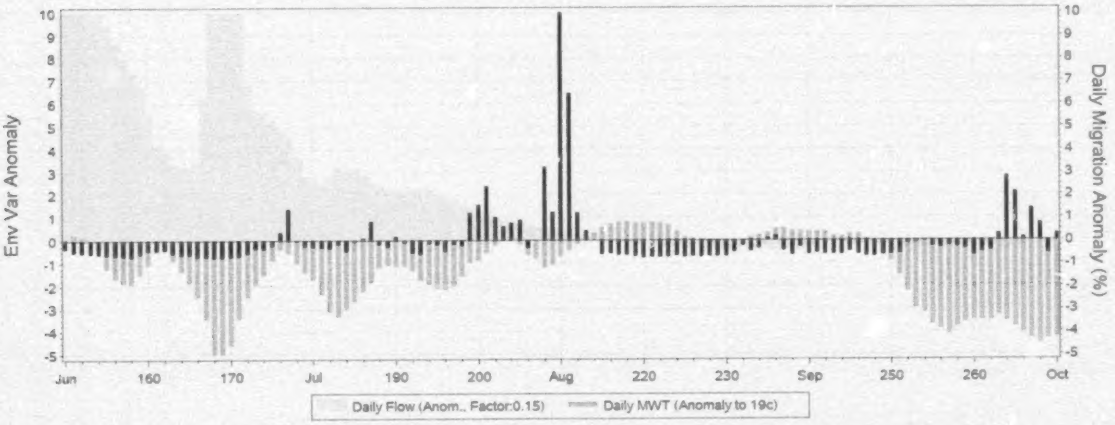
1984 GCL Sockeye Migration Conditions: PDO/ENSO: Warm/Cool Jun-Sep MWT: 17.4c Total Migrants: 133310
Zero-Line Thresholds: Daily Migrants: 0.79% MWT: 19c Flow: 24 cms



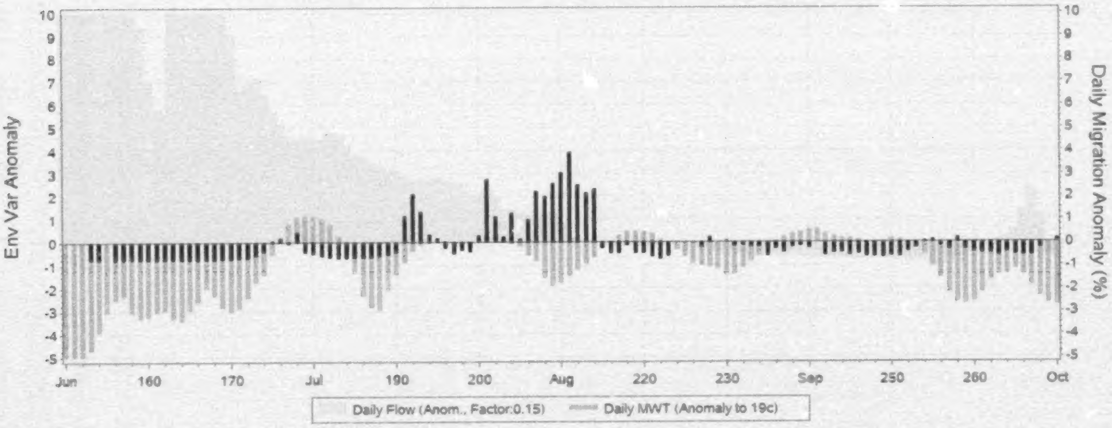
1985 GCL Sockeye Migration Conditions: PDO/ENSO: Warm/Cool Jun-Sep MWT: 18.1c Total Migrants: 120274
Zero-Line Thresholds: Daily Migrants: 0.79% MWT: 19c Flow: 24 cms



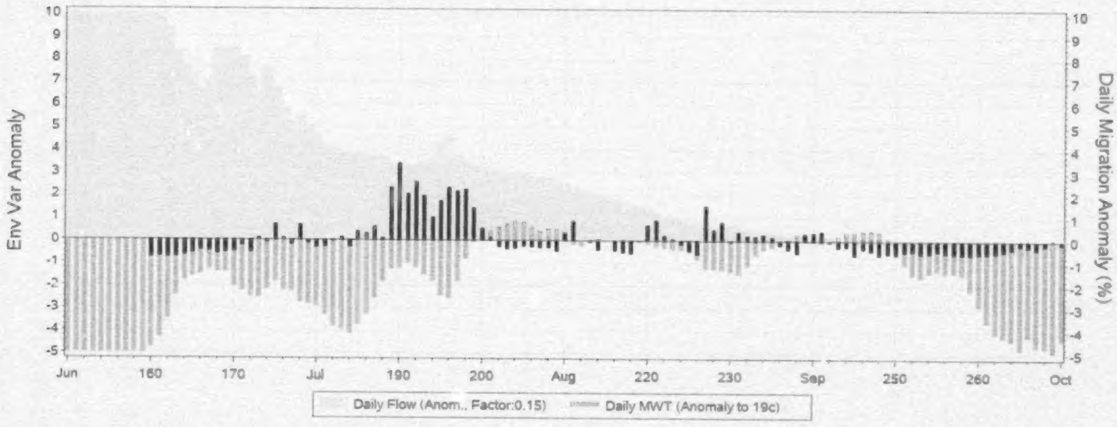
1986 GCL Sockeye Migration Conditions: PDO/ENSO: Warm/Neutral Jun-Sep MWT: 18.2c Total Migrants: 137807
Zero-Line Thresholds: Daily Migrants: 0.79% MWT: 19c Flow: 24 cms



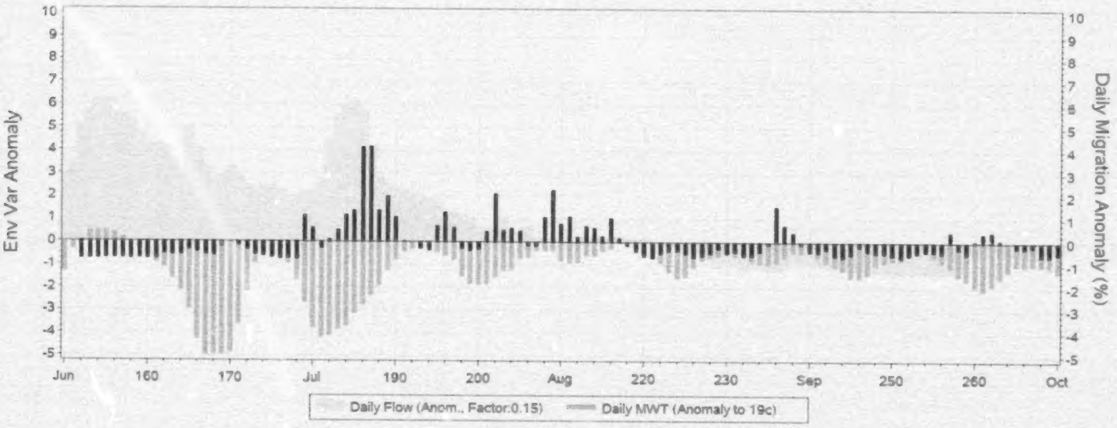
1987 GCL Sockeye Migration Conditions: PDO/ENSO: Warm/Warm Jun-Sep MWT: 18.3c Total Migrants: 290715
Zero-Line Thresholds: Daily Migrants: 0.79% MWT: 19c Flow: 24 cms



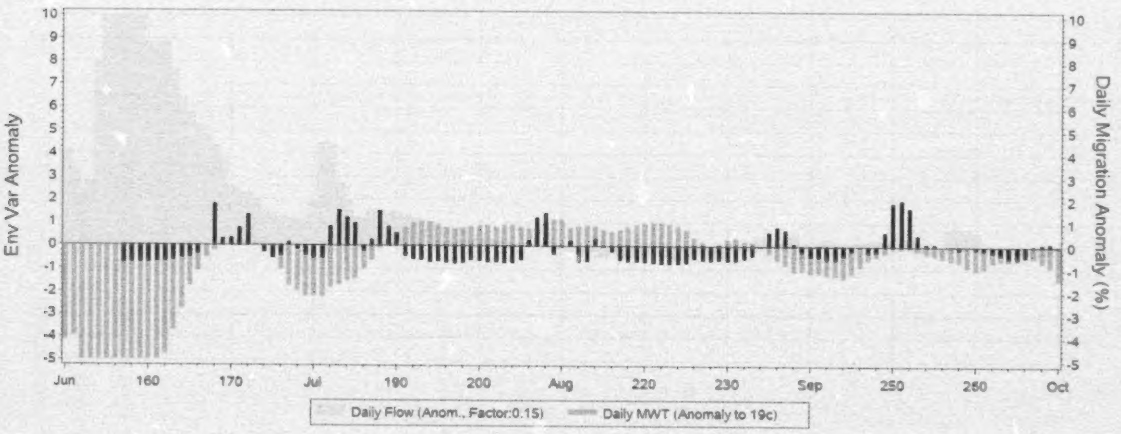
1988 GCL Sockeye Migration Conditions: PDO/ENSO: Warm/Warm Jun-Sep MWT: 17.5c Total Migrants: 206676
Zero-Line Thresholds: Daily Migrants: 0.79% MWT: 19c Flow: 24 cms



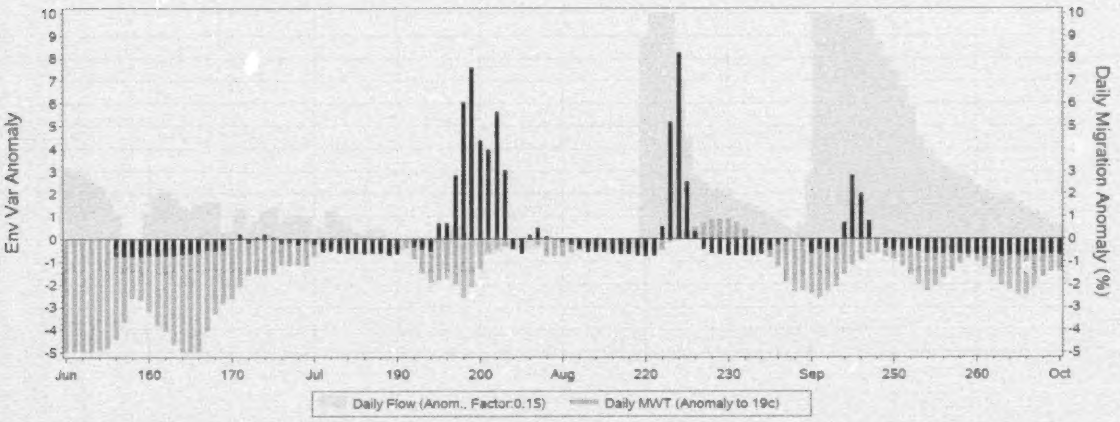
1989 GCL Sockeye Migration Conditions: PDO/ENSO: Warm/Cool Jun-Sep MWT: 18.1c Total Migrants: 241263
Zero-Line Thresholds: Daily Migrants: 0.79% MWT: 19c Flow: 24 cms



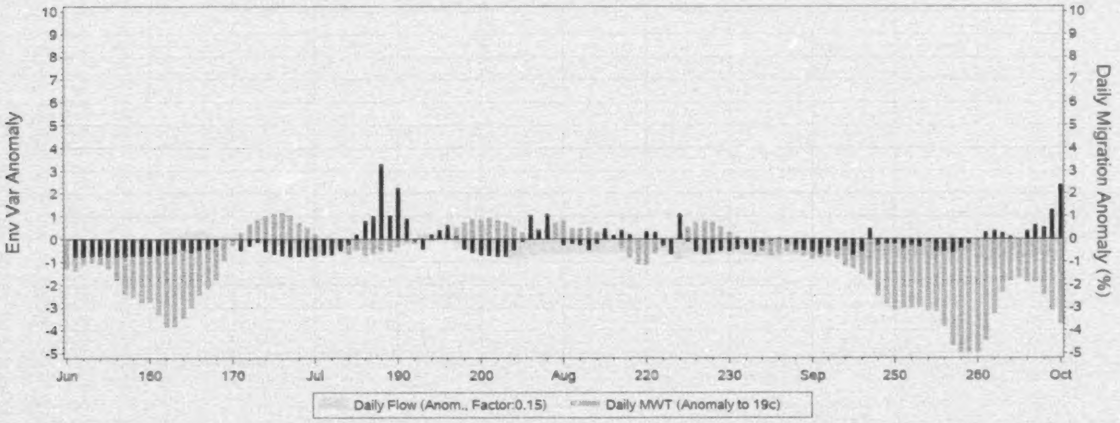
1990 GCL Sockeye Migration Conditions: PDO/ENSO: Warm/Neutral Jun-Sep MWT: 18.9c Total Migrants: 179604
Zero-Line Thresholds: Daily Migrants: 0.79% MWT: 19c Flow: 24 cms



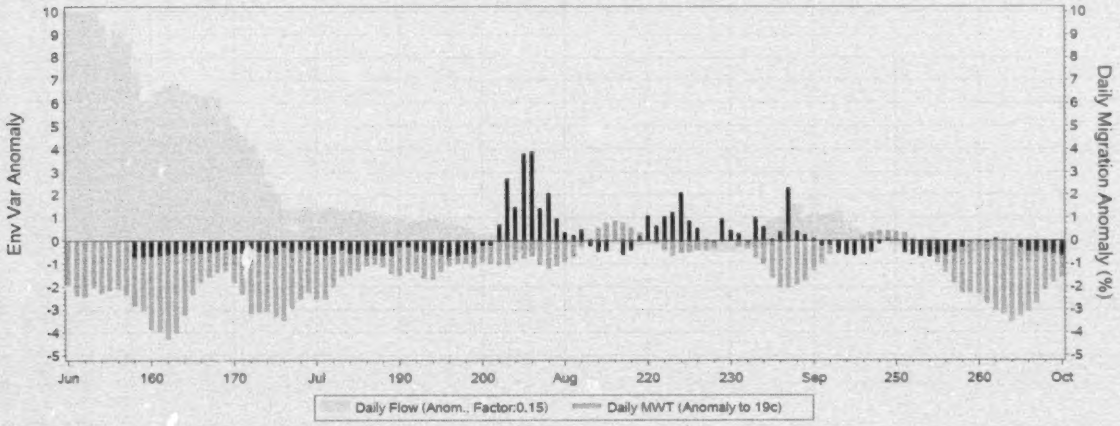
1991 GCL Sockeye Migration Conditions: PDO/ENSO: Warm/Warm Jun-Sep MWT: 17.8c Total Migrants: 433390
Zero-Line Thresholds: Daily Migrants: 0.79% MWT: 19c Flow: 24 cms



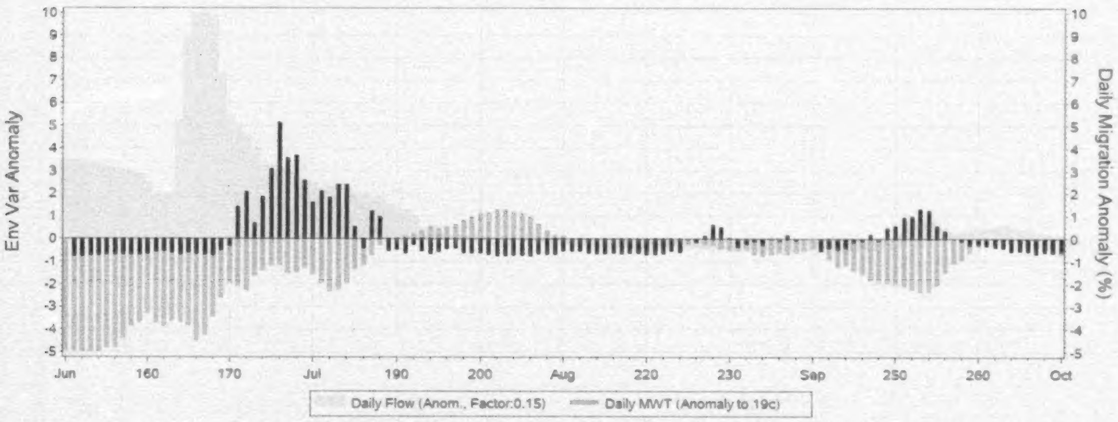
1992 GCL Sockeye Migration Conditions: PDO/ENSO: Warm/Warm Jun-Sep MWT: 18.5c Total Migrants: 195118
Zero-Line Thresholds: Daily Migrants: 0.79% MWT: 19c Flow: 24 cms



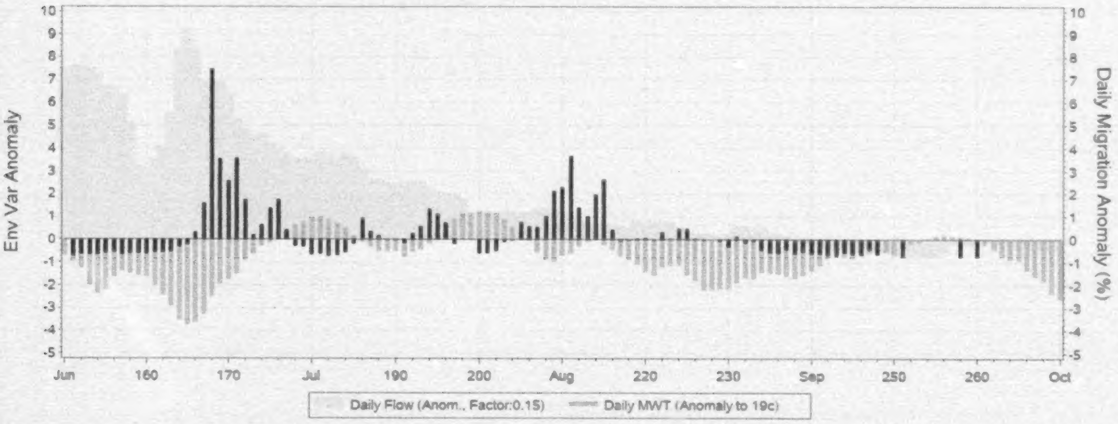
1993 GCL Sockeye Migration Conditions: PDO/ENSO: Warm/Warm Jun-Sep MWT: 17.9c Total Migrants: 237539
Zero-Line Thresholds: Daily Migrants: 0.79% MWT: 19c Flow: 24 cms



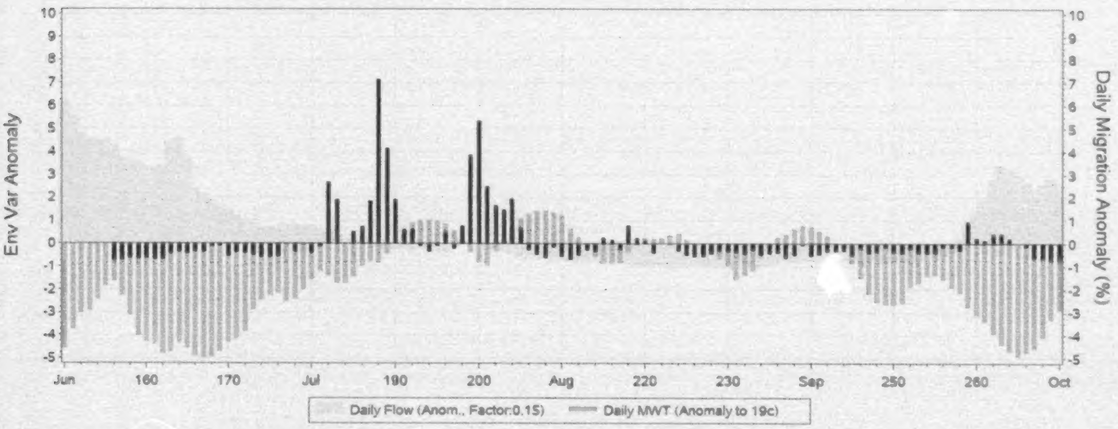
1994 GCL Sockeye Migration Conditions: PDO/ENSO: Warm/Neutral Jun-Sep MWT: 18.3c Total Migrants: 113493
Zero-Line Thresholds: Daily Migrants: 0.79% MWT: 19c Flow: 24 cms



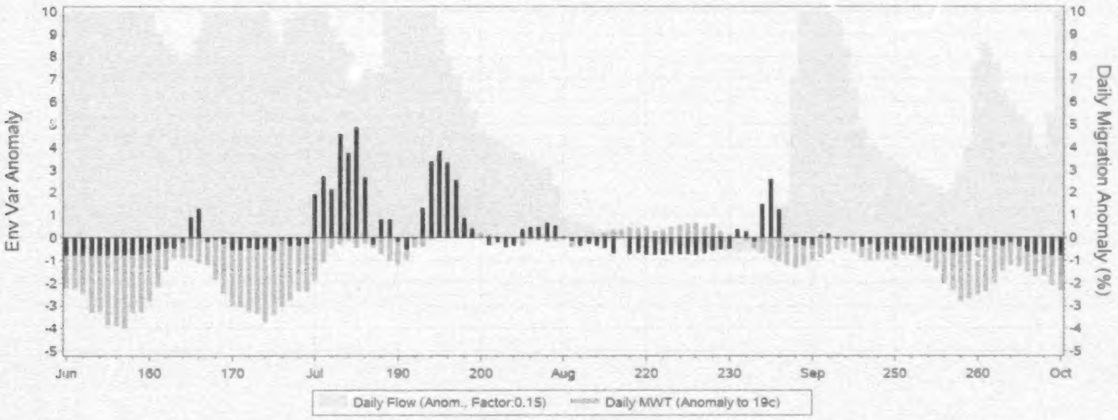
1995 GCL Sockeye Migration Conditions: PDO/ENSO: Warm/Warm Jun-Sep MWT: 18.6c Total Migrants: 64093
Zero-Line Thresholds: Daily Migrants: 0.79% MWT: 19c Flow: 24 cms



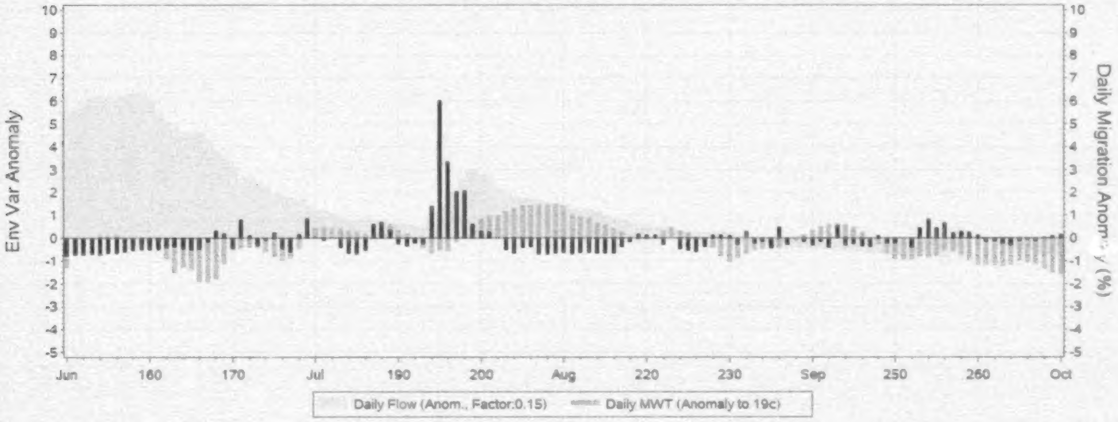
1996 GCL Sockeye Migration Conditions: PDO/ENSO: Warm/Neutral Jun-Sep MWT: 18.0c Total Migrants: 165025
Zero-Line Thresholds: Daily Migrants: 0.79% MWT: 19c Flow: 24 cms



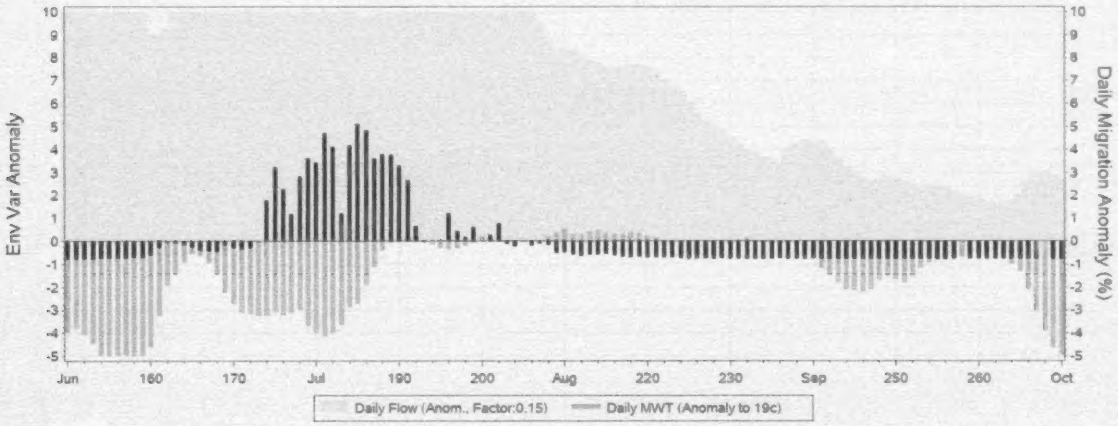
1997 GCL Sockeye Migration Conditions: PDO/ENSO: Warm/Neutral Jun-Sep MWT: 18.3c Total Migrants: 172409.45559
Zero-Line Thresholds: Daily Migrants: 0.79% MWT: 19c Flow: 24 cms

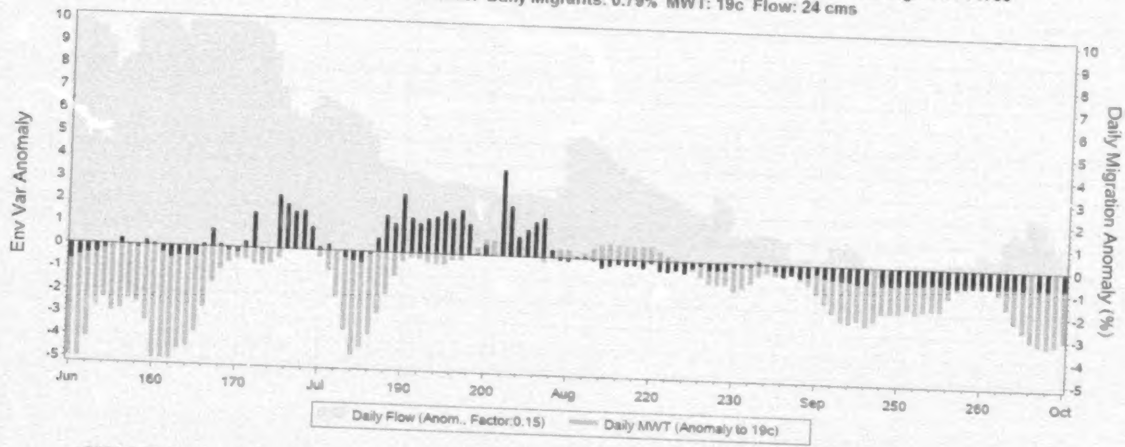


1998 GCL Sockeye Migration Conditions: PDO/ENSO: Warm/Warm Jun-Sep MWT: 19.4c Total Migrants: 274279
Zero-Line Thresholds: Daily Migrants: 0.79% MWT: 19c Flow: 24 cms

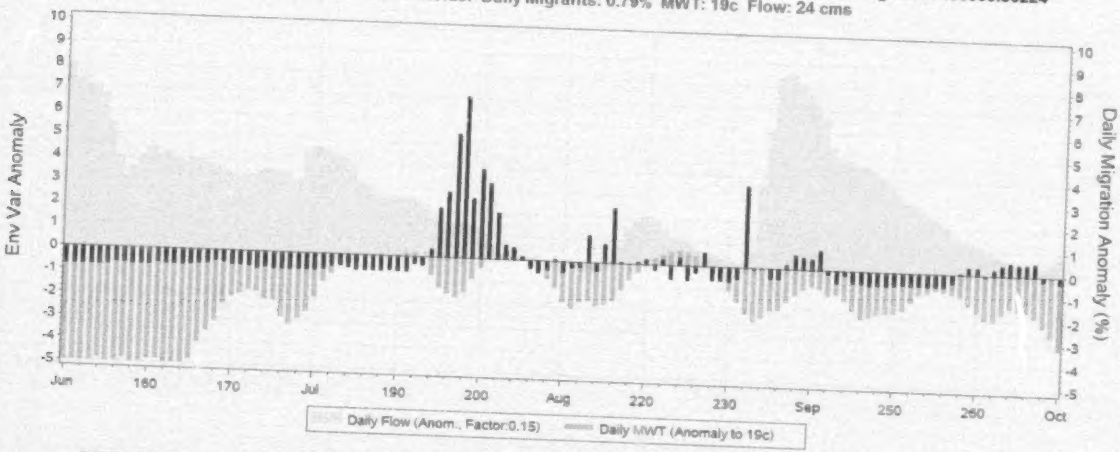


1999 GCL Sockeye Migration Conditions: PDO/ENSO: Cool/Cool Jun-Sep MWT: 18.0c Total Migrants: 211111.27928
Zero-Line Thresholds: Daily Migrants: 0.79% MWT: 19c Flow: 24 cms

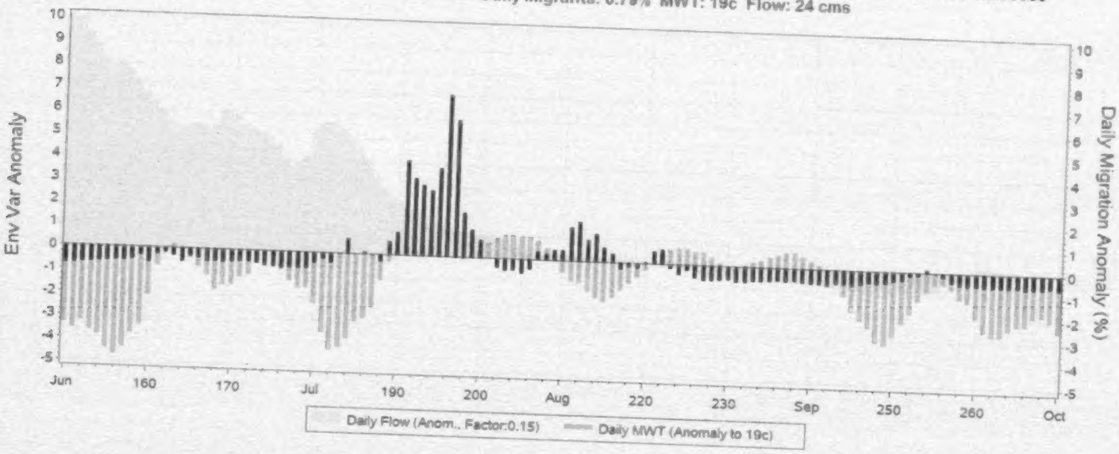




2000 GCL Sockeye Migration Conditions: PDO/ENSO: Cool/Cool Jun-Sep MWT: 18.1c Total Migrants: 71730
Zero-Line Thresholds: Daily Migrants: 0.79% MWT: 19c Flow: 24 cms

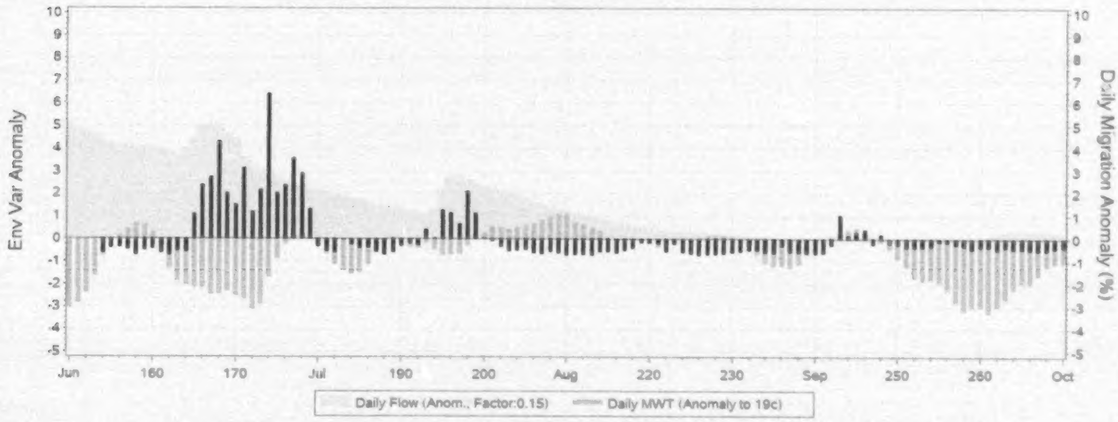


2001 GCL Sockeye Migration Conditions: PDO/ENSO: Cool/Neutral Jun-Sep MWT: 17.6c Total Migrants: 406509.86224
Zero-Line Thresholds: Daily Migrants: 0.79% MWT: 19c Flow: 24 cms

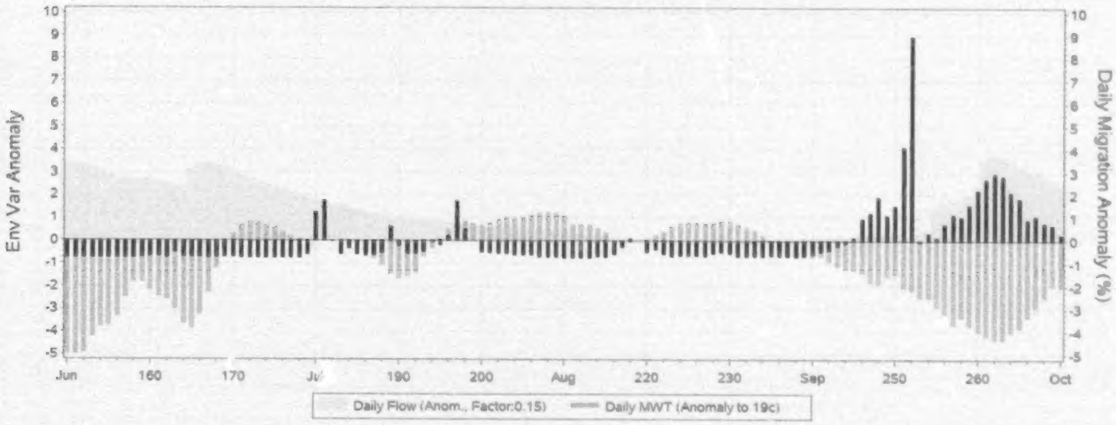


2002 GCL Sockeye Migration Conditions: PDO/ENSO: Cool/Neutral Jun-Sep MWT: 16.4c Total Migrants: 281335.78066
Zero-Line Thresholds: Daily Migrants: 0.79% MWT: 19c Flow: 24 cms

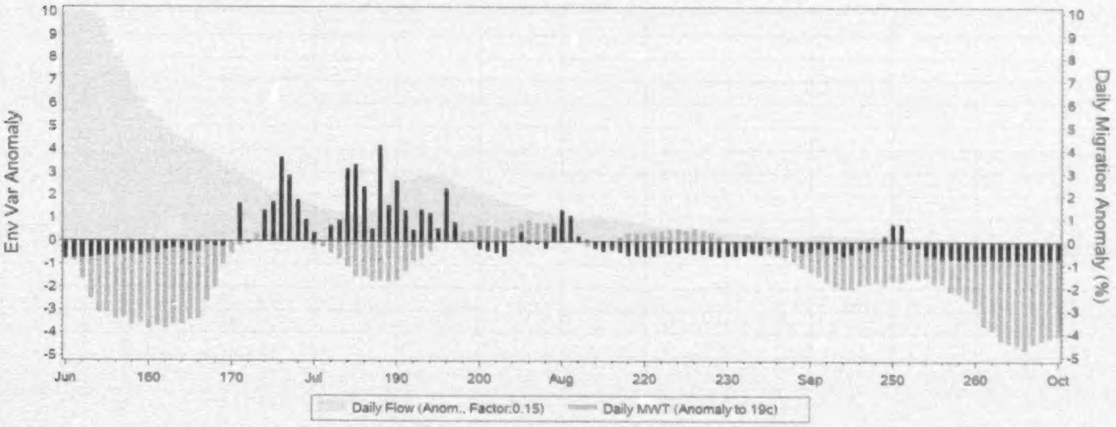
2003 GCL Sockeye Migration Conditions: PDO/ENSO: Warm/Warm Jun-Sep MWT: 18.7c Total Migrants: 241754.63071
Zero-Line Thresholds: Daily Migrants: 0.79% MWT: 19c Flow: 24 cms



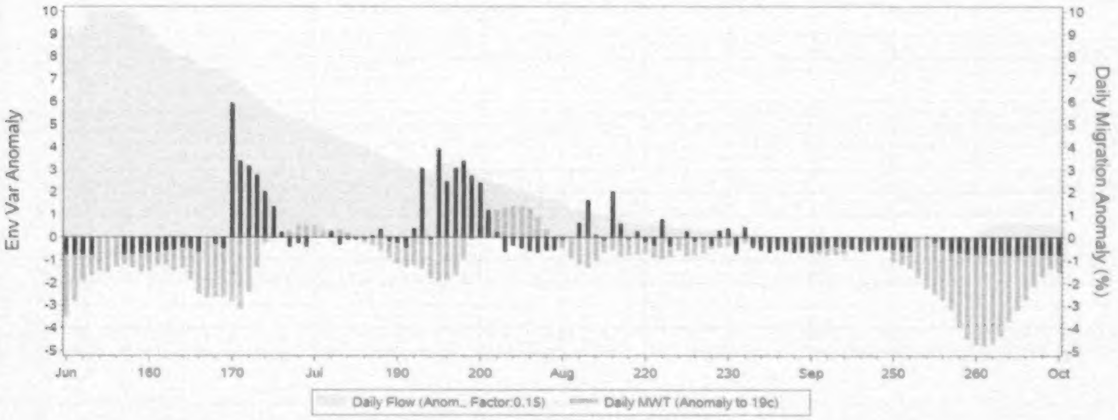
2004 GCL Sockeye Migration Conditions: PDO/ENSO: Warm/Warm Jun-Sep MWT: 18.6c Total Migrants: 205618
Zero-Line Thresholds: Daily Migrants: 0.79% MWT: 19c Flow: 24 cms



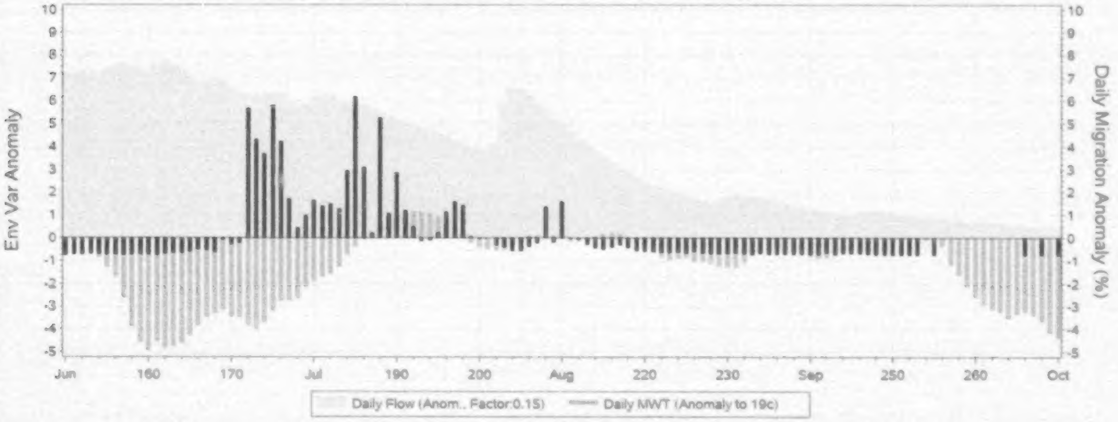
2005 GCL Sockeye Migration Conditions: PDO/ENSO: Warm/Warm Jun-Sep MWT: 18.3c Total Migrants: 189122.42087
Zero-Line Thresholds: Daily Migrants: 0.79% MWT: 19c Flow: 24 cms



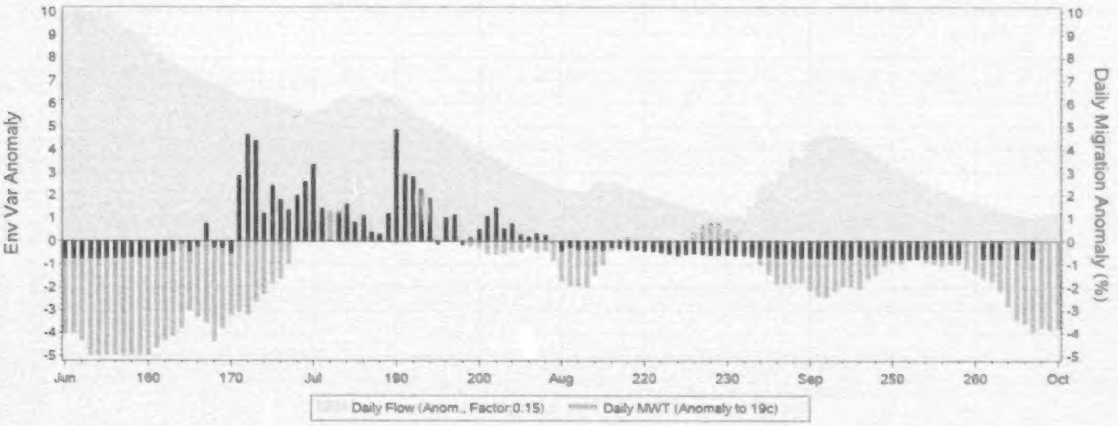
2006 GCL Sockeye Migration Conditions: PDO/ENSO: Cool/Neutral Jun-Sep MWT: 18.3c Total Migrants: 131567.72969
Zero-Line Thresholds: Daily Migrants: 0.79% MWT: 19c Flow: 24 cms



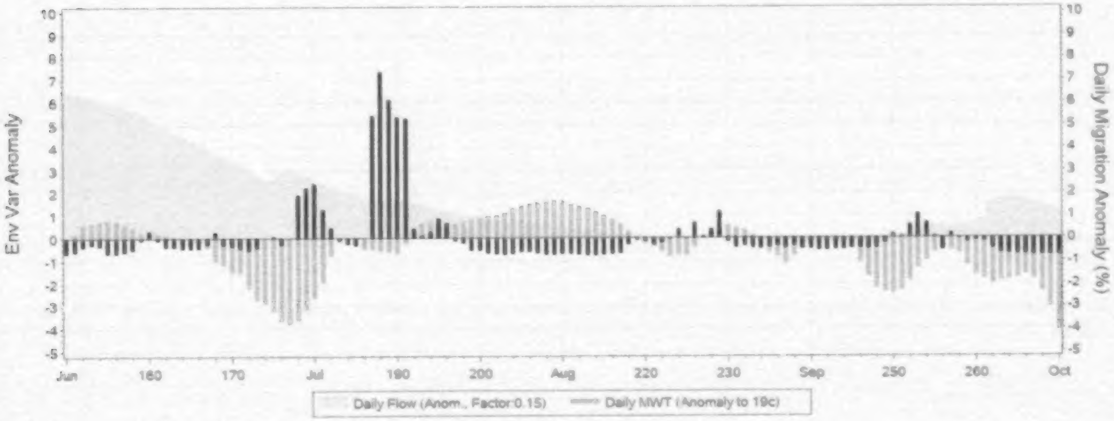
2007 GCL Sockeye Migration Conditions: PDO/ENSO: Cool/Warm Jun-Sep MWT: 18.1c Total Migrants: 76372.666667
Zero-Line Thresholds: Daily Migrants: 0.79% MWT: 19c Flow: 24 cms



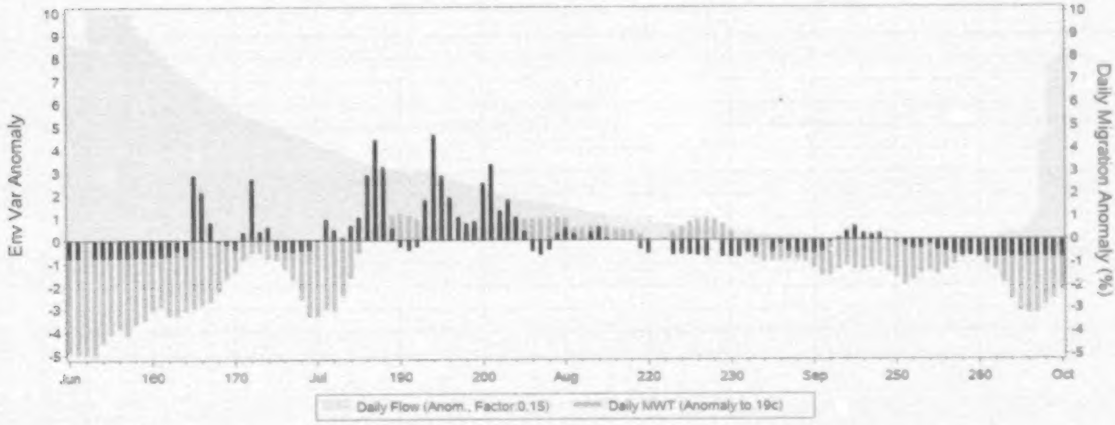
2008 GCL Sockeye Migration Conditions: PDO/ENSO: Cool/Cool Jun-Sep MWT: 17.9c Total Migrants: 74024.006757
Zero-Line Thresholds: Daily Migrants: 0.79% MWT: 19c Flow: 24 cms



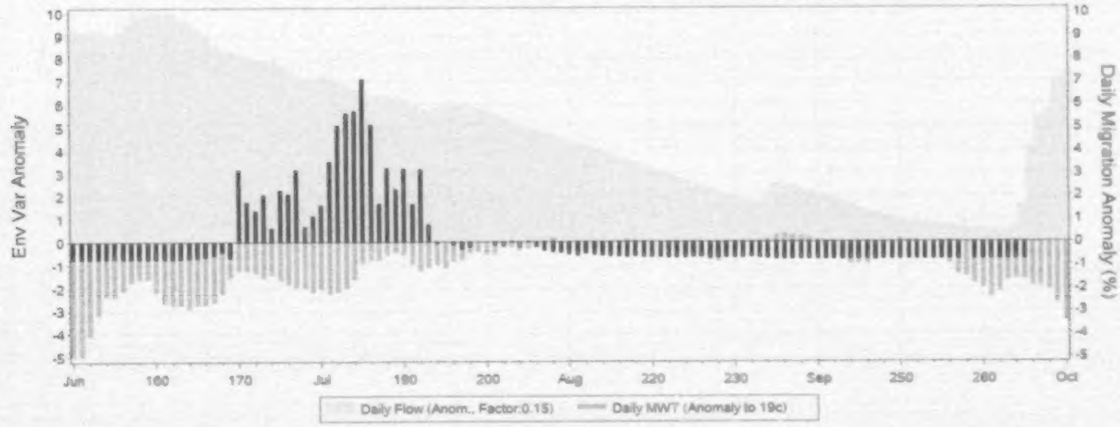
2009 GCL Sockeye Migration Conditions: PDO/ENSO: Cool/Neutral Jun-Sep MWT: 19.2c Total Migrants: 219744.28766
Zero-Line Thresholds: Daily Migrants: 0.79% MWT: 19c Flow: 24 cms

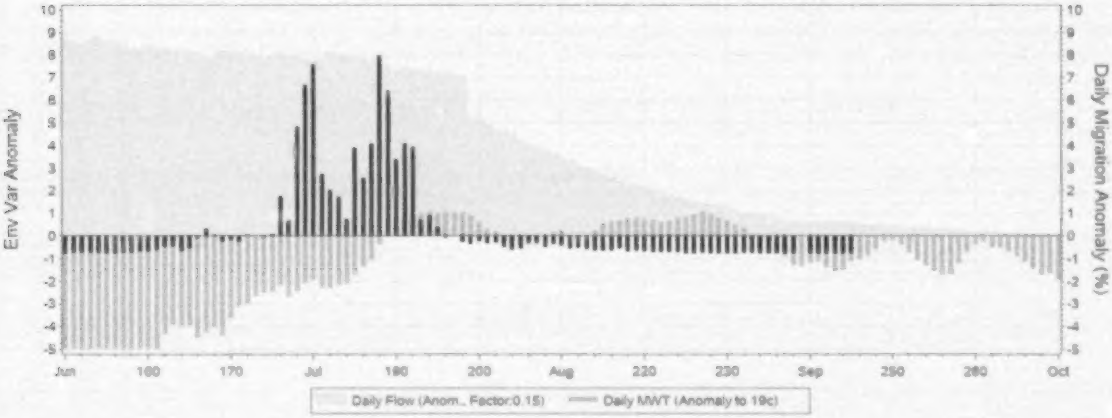


2010 GCL Sockeye Migration Conditions: PDO/ENSO: Warm/Warm Jun-Sep MWT: 18.5c Total Migrants: 335204.12834
Zero-Line Thresholds: Daily Migrants: 0.79% MWT: 19c Flow: 24 cms



2011 GCL Sockeye Migration Conditions: PDO/ENSO: 2011/Unknown Jun-Sep MWT: 18.3c Total Migrants: 445438
Zero-Line Thresholds: Daily Migrants: 0.79% MWT: 19c Flow: 24 cms

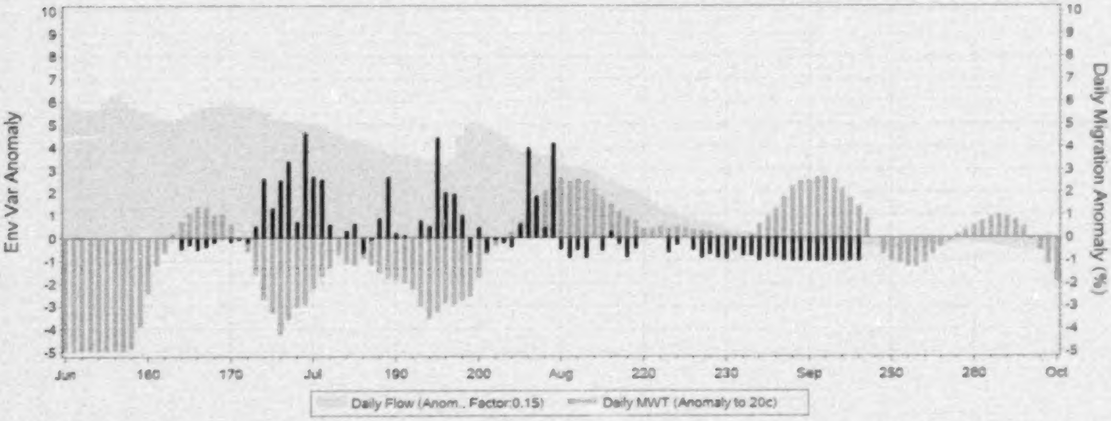




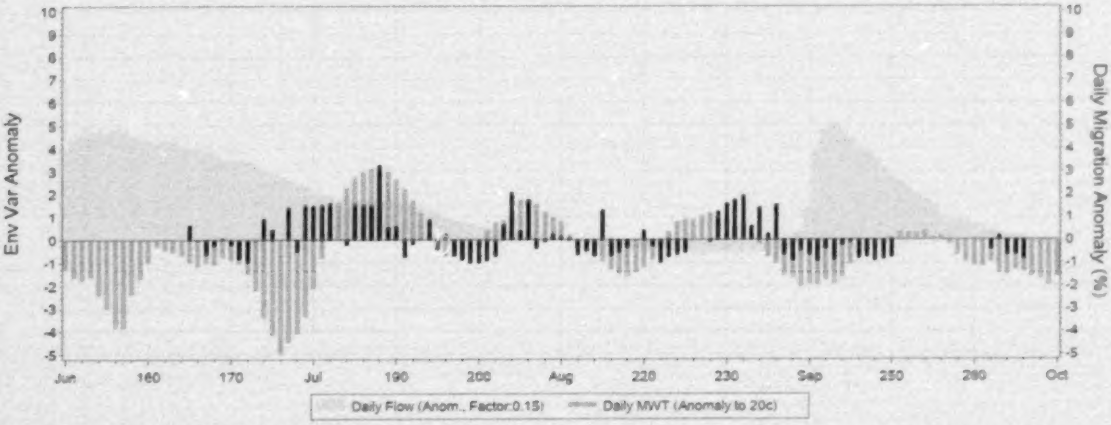
2012 GCL Sockeye Migration Conditions: PDO/ENSO: 2012/Unknown Jun-Sep MWT: 18.5c Total Migrants: 149202
Zero-Line Thresholds: Daily Migrants: 0.79% MWT: 19c Flow: 24 cms

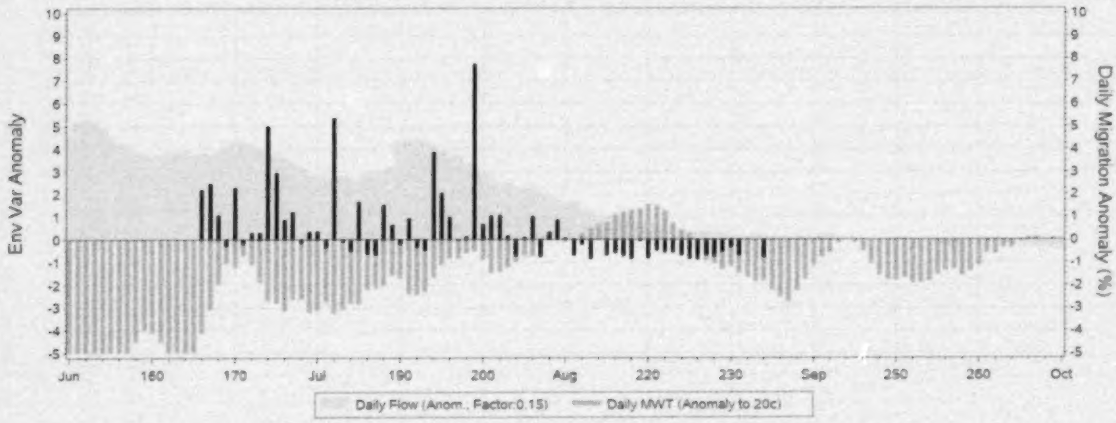
Appendix C. Annual anomaly plots for Sproat Lake sockeye migration, water temperature, and river discharge. Zero-line thresholds: (a) Daily migration rate = 1.07% (75th percentile of non-zero daily migration rates (1974-2012); (b) Water temperature = 20°C; Discharge = 10 cms.

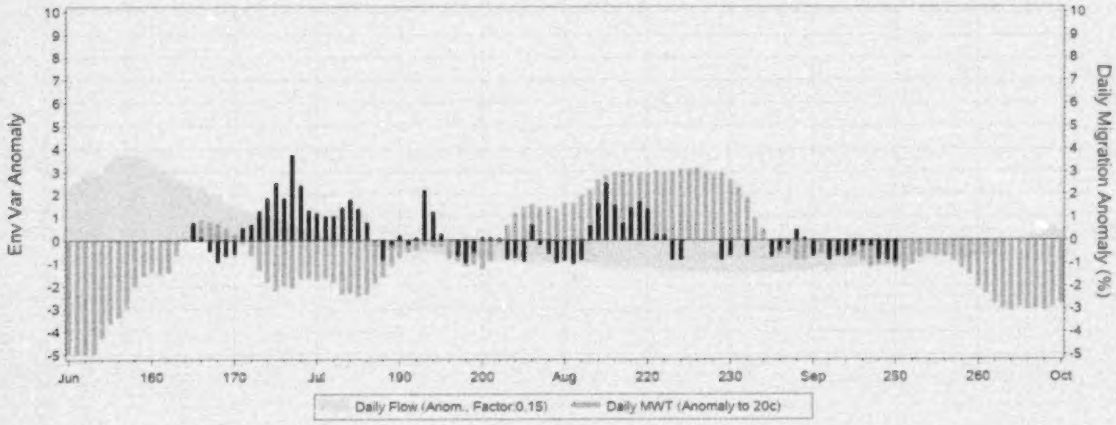
1974 SPR Sockeye Migration Conditions: PDO/ENSO: Cool/Cool Jun-Sep MWT: 19.4c Total Migrants: 56011
Zero-Line Thresholds: Daily Migrants: 1.07% MWT: 20c Flow: 10 cms

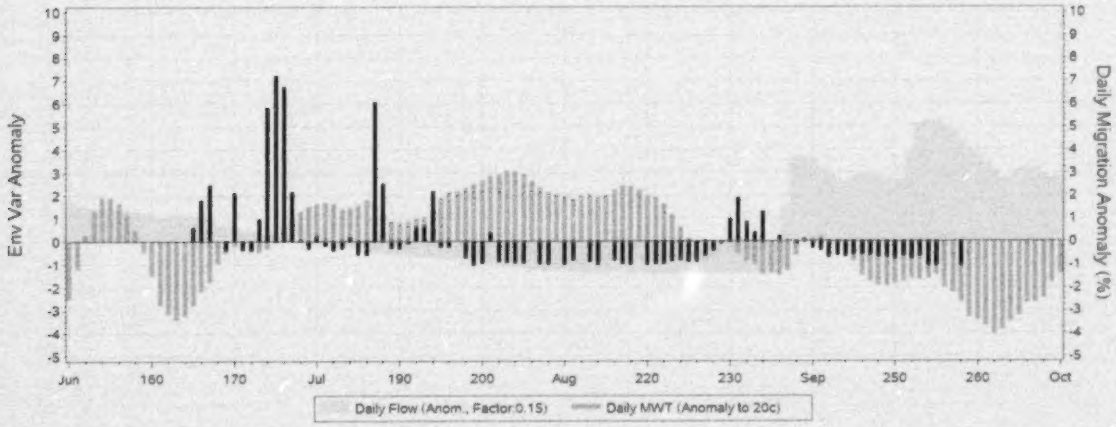


1975 SPR Sockeye Migration Conditions: PDO/ENSO: Cool/Neutral Jun-Sep MWT: 19.4c Total Migrants: 55069
Zero-Line Thresholds: Daily Migrants: 1.07% MWT: 20c Flow: 10 cms

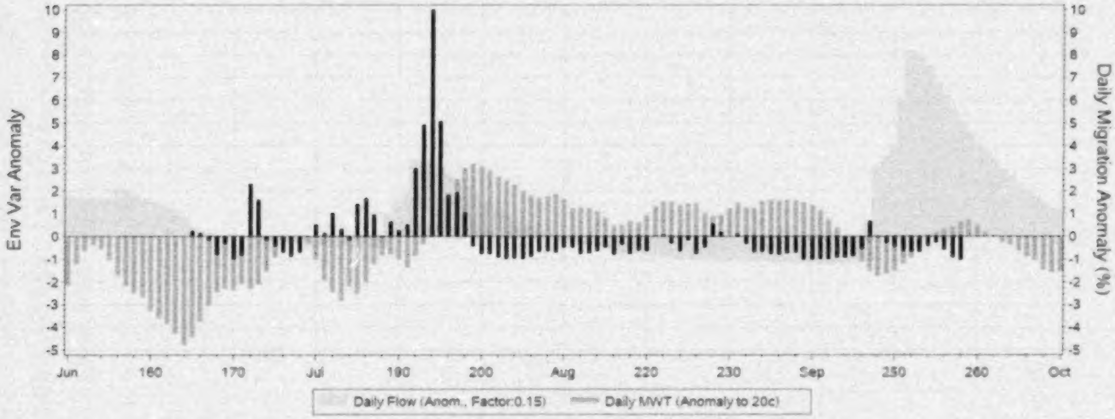



1976 SPR Sockeye Migration Conditions: PDO/ENSO: Cool/Cool Jun-Sep MWT: 18.1c Total Migrants: 47404
Zero-Line Thresholds: Daily Migrants: 1.07% MWT: 20c Flow: 10 cms

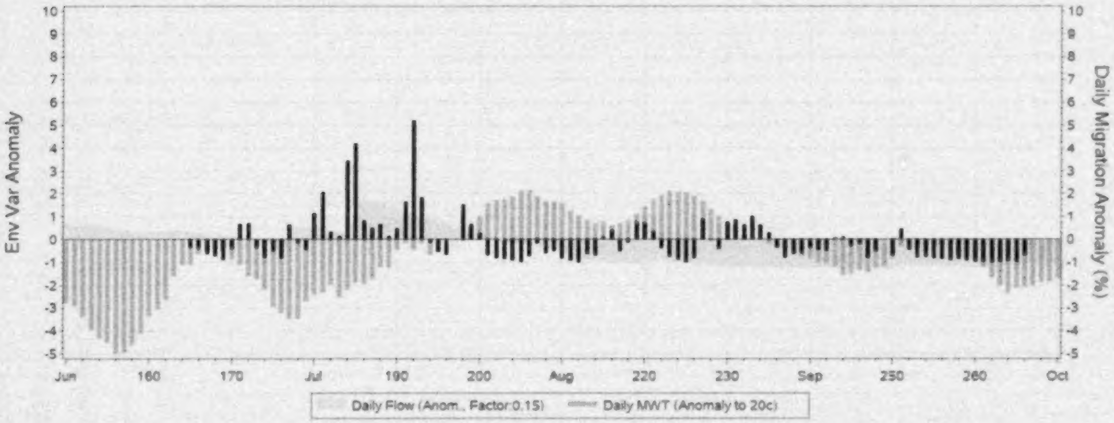

1977 SPR Sockeye Migration Conditions: PDO/ENSO: Warm/Warm Jun-Sep MWT: 19.4c Total Migrants: 64219
Zero-Line Thresholds: Daily Migrants: 1.07% MWT: 20c Flow: 10 cms


1978 SPR Sockeye Migration Conditions: PDO/ENSO: Warm/Warm Jun-Sep MWT: 19.9c Total Migrants: 32580
Zero-Line Thresholds: Daily Migrants: 1.07% MWT: 20c Flow: 10 cms

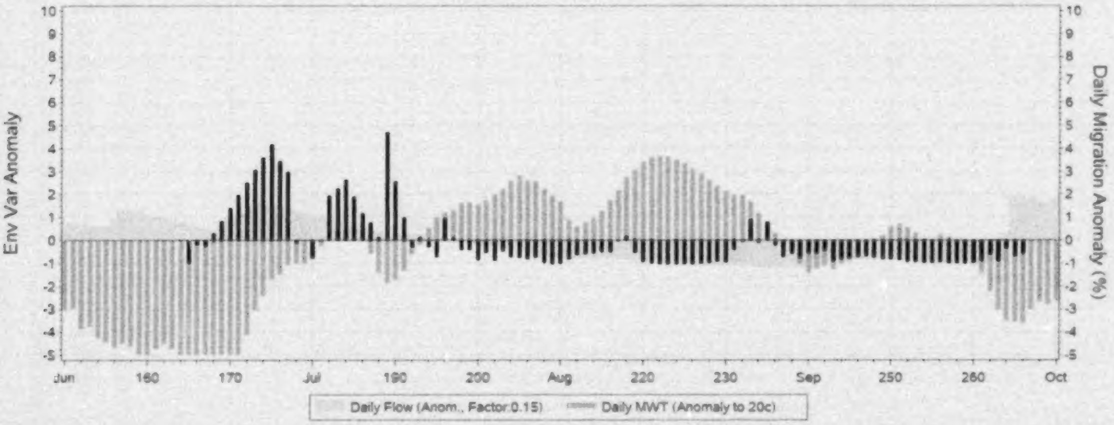
1979 SPR Sockeye Migration Conditions: PDO/ENSO: Warm/Neutral Jun-Sep MWT: 19.7c Total Migrants: 73473
Zero-Line Thresholds: Daily Migrants: 1.07% MWT: 20c Flow: 10 cms



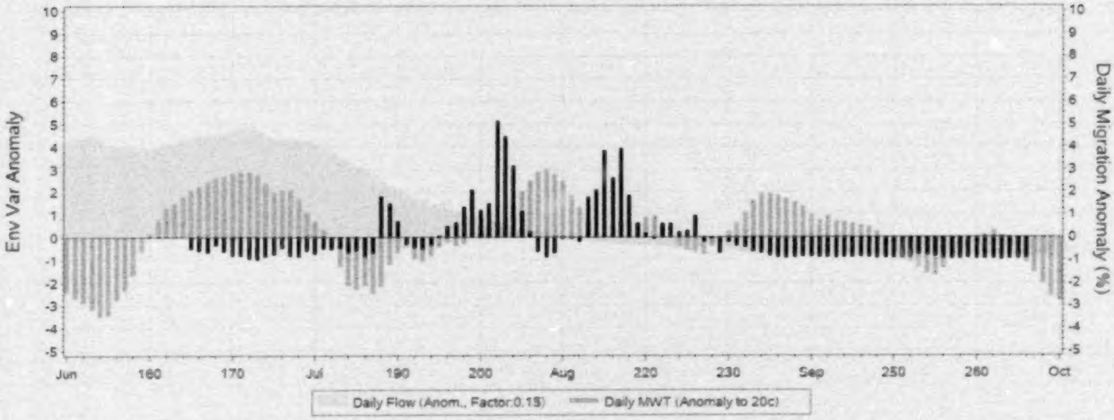
1980 SPR Sockeye Migration Conditions: PDO/ENSO: Warm/Warm Jun-Sep MWT: 19.2c Total Migrants: 136033
Zero-Line Thresholds: Daily Migrants: 1.07% MWT: 20c Flow: 10 cms



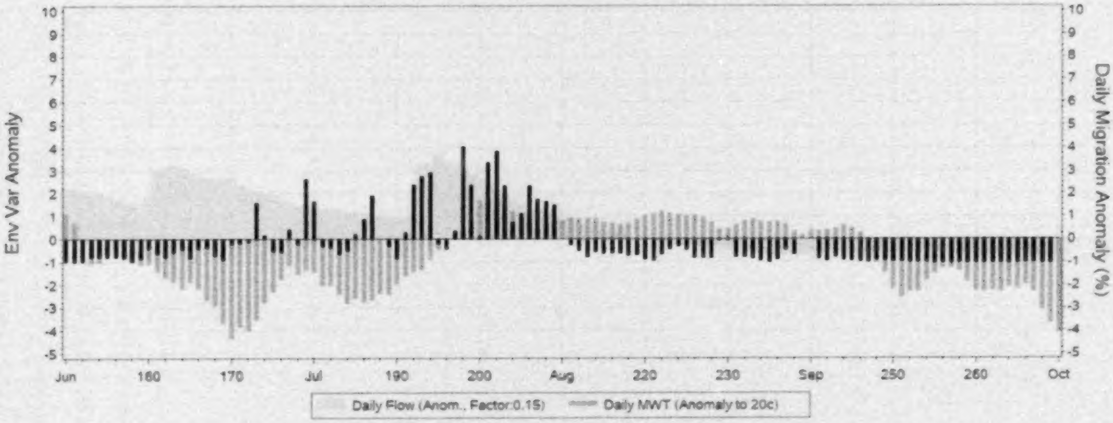
1981 SPR Sockeye Migration Conditions: PDO/ENSO: Warm/Neutral Jun-Sep MWT: 19.3c Total Migrants: 130812
Zero-Line Thresholds: Daily Migrants: 1.07% MWT: 20c Flow: 10 cms



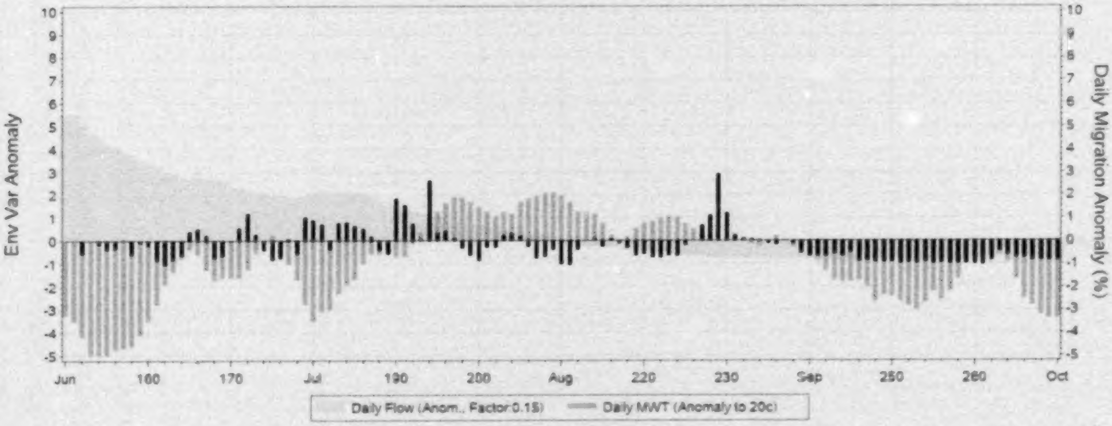
1982 SPR Sockeye Migration Conditions: PDO/ENSO: Warm/Neutral Jun-Sep MWT: 20.1c Total Migrants: 224693
Zero-Line Thresholds: Daily Migrants: 1.07% MWT: 20c Flow: 10 cms

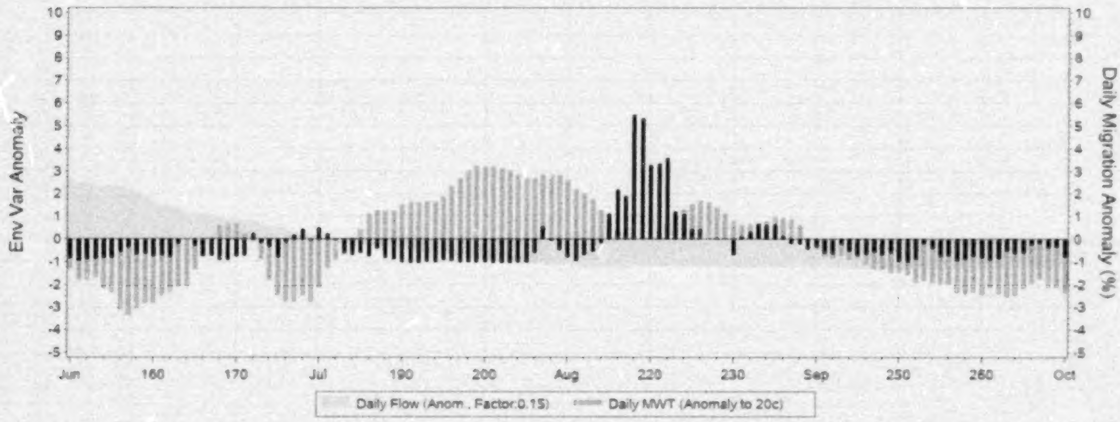


1983 SPR Sockeye Migration Conditions: PDO/ENSO: Warm/Warm Jun-Sep MWT: 19.5c Total Migrants: 257793
Zero-Line Thresholds: Daily Migrants: 1.07% MWT: 20c Flow: 10 cms

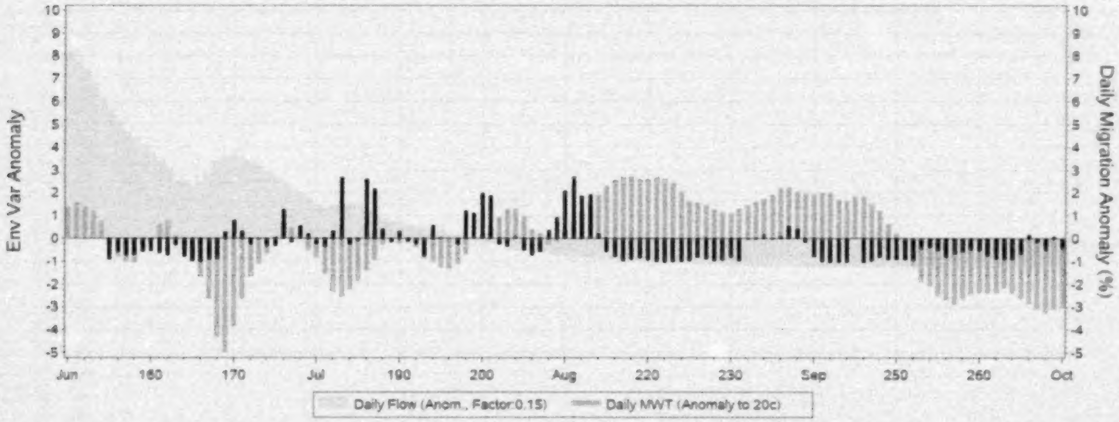


1984 SPR Sockeye Migration Conditions: PDO/ENSO: Warm/Cool Jun-Sep MWT: 19.0c Total Migrants: 89100
Zero-Line Thresholds: Daily Migrants: 1.07% MWT: 20c Flow: 10 cms

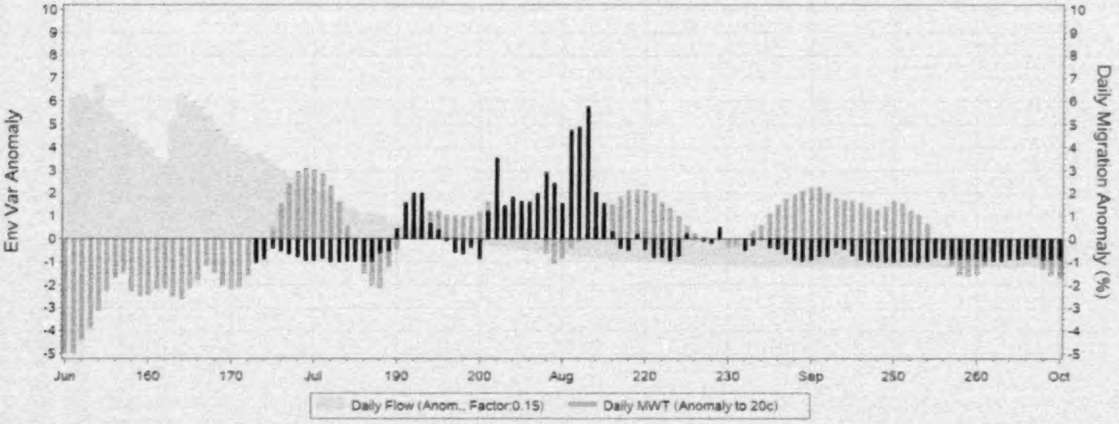




1985 SPR Sockeye Migration Conditions: PDO/ENSO: Warm/Cool Jun-Sep MWT: 19.7c Total Migrants: 146951
Zero-Line Thresholds: Daily Migrants: 1.07% MWT: 20c Flow: 10 cms

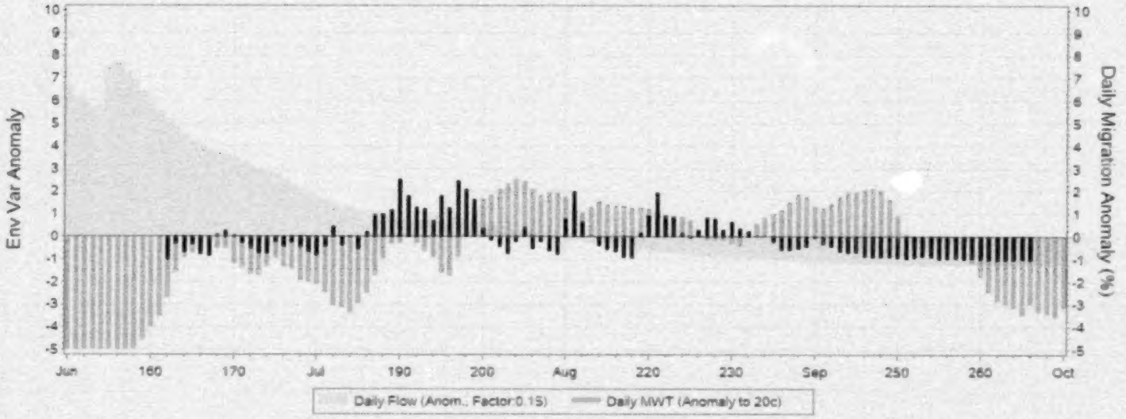


1986 SPR Sockeye Migration Conditions: PDO/ENSO: Warm/Neutral Jun-Sep MWT: 19.8c Total Migrants: 192941
Zero-Line Thresholds: Daily Migrants: 1.07% MWT: 20c Flow: 10 cms

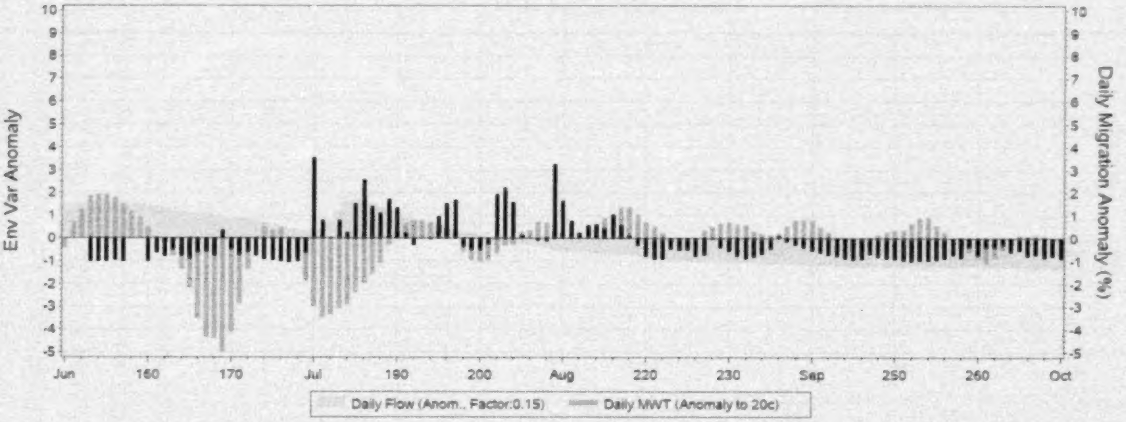


1987 SPR Sockeye Migration Conditions: PDO/ENSO: Warm/Warm Jun-Sep MWT: 20.0c Total Migrants: 151835
Zero-Line Thresholds: Daily Migrants: 1.07% MWT: 20c Flow: 10 cms

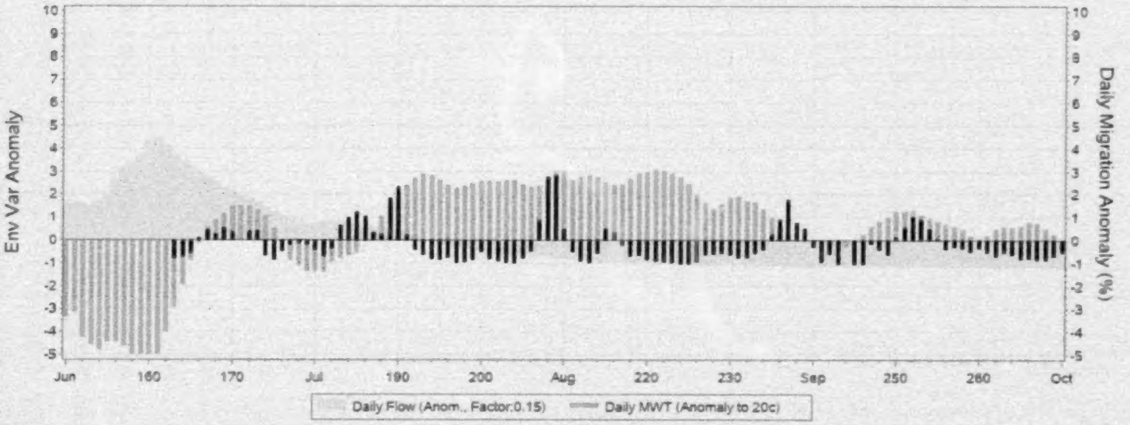
1988 SPR Sockeye Migration Conditions: PDO/ENSO: Warm/Warm Jun-Sep MWT: 19.1c Total Migrants: 235417
Zero-Line Thresholds: Daily Migrants: 1.07% MWT: 20c Flow: 10 cms

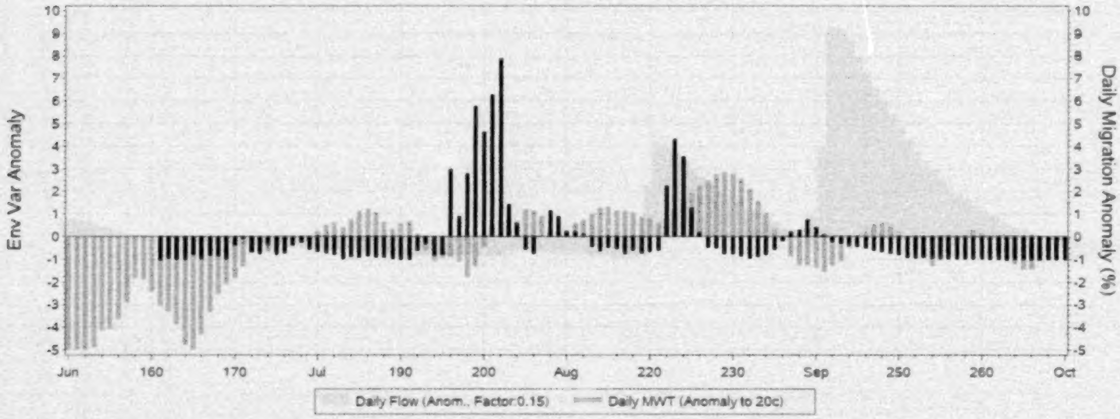


1989 SPR Sockeye Migration Conditions: PDO/ENSO: Warm/Cool Jun-Sep MWT: 19.7c Total Migrants: 167987
Zero-Line Thresholds: Daily Migrants: 1.07% MWT: 20c Flow: 10 cms

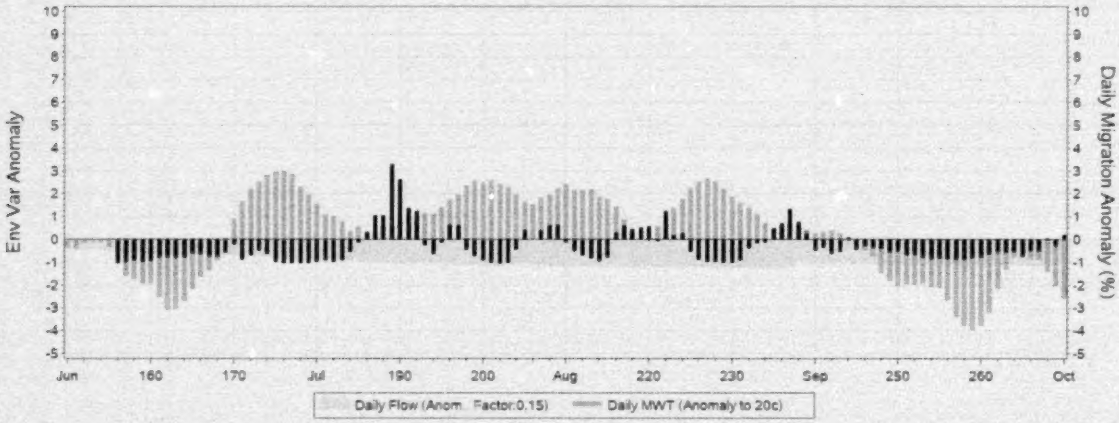


1990 SPR Sockeye Migration Conditions: PDO/ENSO: Warm/Neutral Jun-Sep MWT: 20.5c Total Migrants: 112790
Zero-Line Thresholds: Daily Migrants: 1.07% MWT: 20c Flow: 10 cms

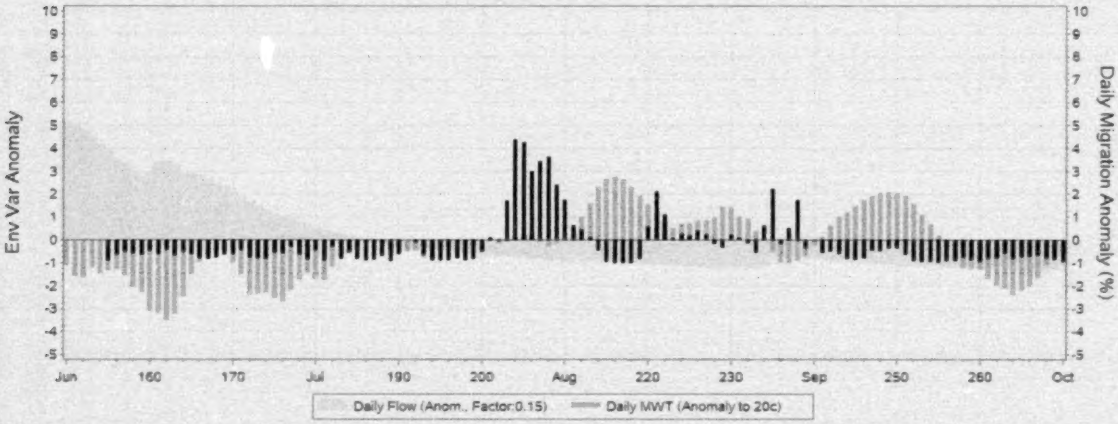




1991 SPR Sockeye Migration Conditions: PDO/ENSO: Warm/Warm Jun-Sep MWT: 19.5c Total Migrants: 209475
Zero-Line Thresholds: Daily Migrants: 1.07% MWT: 20c Flow: 10 cms

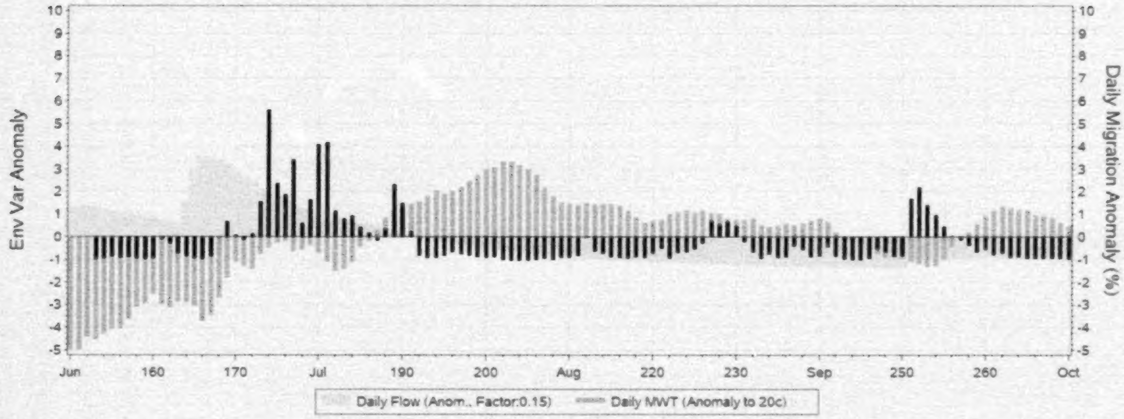


1992 SPR Sockeye Migration Conditions: PDO/ENSO: Warm/Warm Jun-Sep MWT: 20.2c Total Migrants: 221938
Zero-Line Thresholds: Daily Migrants: 1.07% MWT: 20c Flow: 10 cms

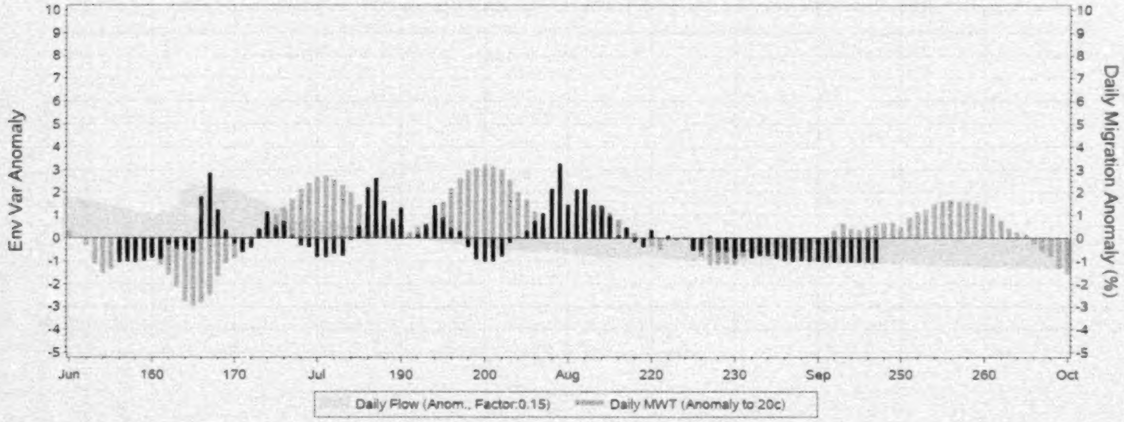


1993 SPR Sockeye Migration Conditions: PDO/ENSO: Warm/Warm Jun-Sep MWT: 19.6c Total Migrants: 205289
Zero-Line Thresholds: Daily Migrants: 1.07% MWT: 20c Flow: 10 cms

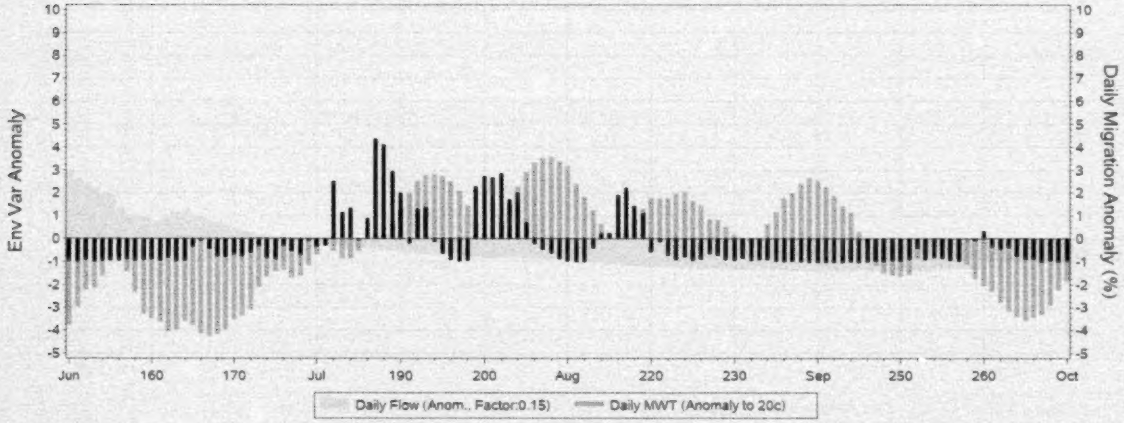
1994 SPR Sockeye Migration Conditions: PDO/ENSO: Warm/Neutral Jun-Sep MWT: 19.9c Total Migrants: 143770
Zero-Line Thresholds: Daily Migrants: 1.07% MWT: 20c Flow: 10 cms



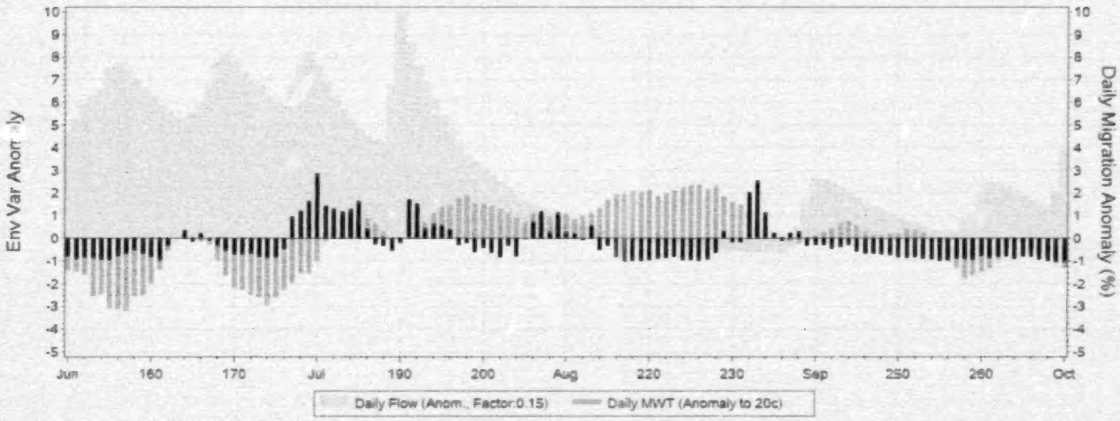
1995 SPR Sockeye Migration Conditions: PDO/ENSO: Warm/Warm Jun-Sep MWT: 20.3c Total Migrants: 102400
Zero-Line Thresholds: Daily Migrants: 1.07% MWT: 20c Flow: 10 cms



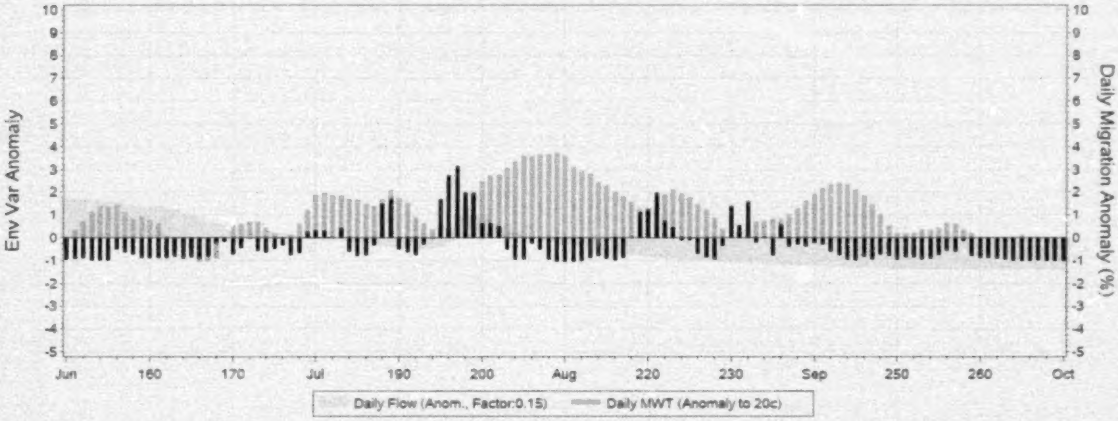
1996 SPR Sockeye Migration Conditions: PDO/ENSO: Warm/Neutral Jun-Sep MWT: 19.6c Total Migrants: 210051
Zero-Line Thresholds: Daily Migrants: 1.07% MWT: 20c Flow: 10 cms



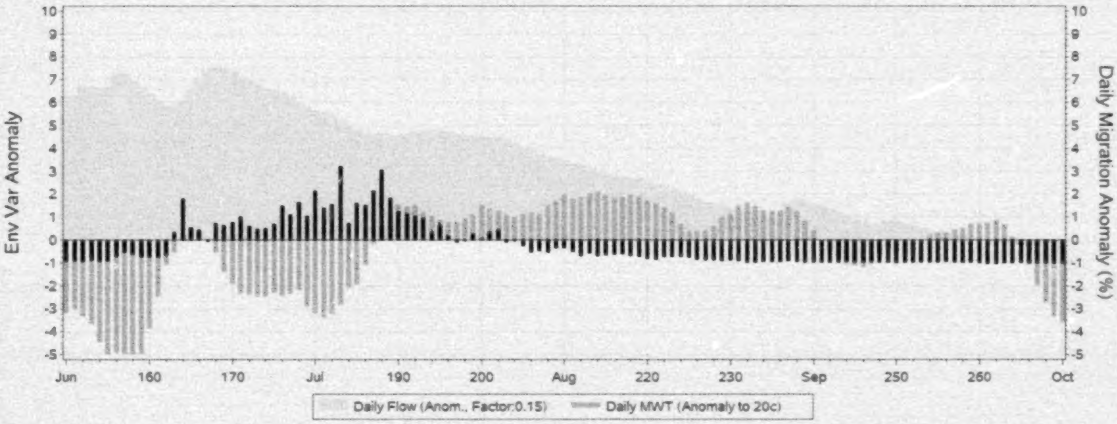
1997 SPR Sockeye Migration Conditions: PDO/ENSO: Warm/Neutral Jun-Sep MWT: 20.0c Total Migrants: 143403
Zero-Line Thresholds: Daily Migrants: 1.07% MWT: 20c Flow: 10 cms



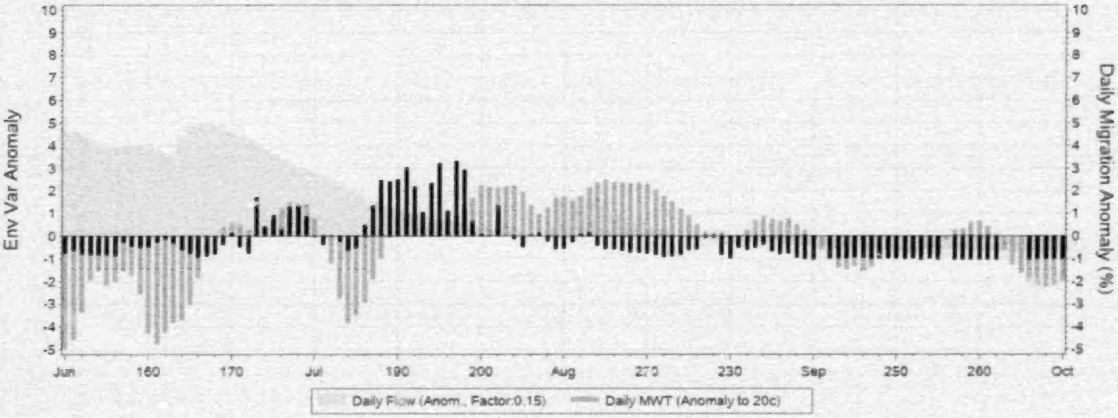
1998 SPR Sockeye Migration Conditions: PDO/ENSO: Warm/Warm Jun-Sep MWT: 21.1c Total Migrants: 274014
Zero-Line Thresholds: Daily Migrants: 1.07% MWT: 20c Flow: 10 cms



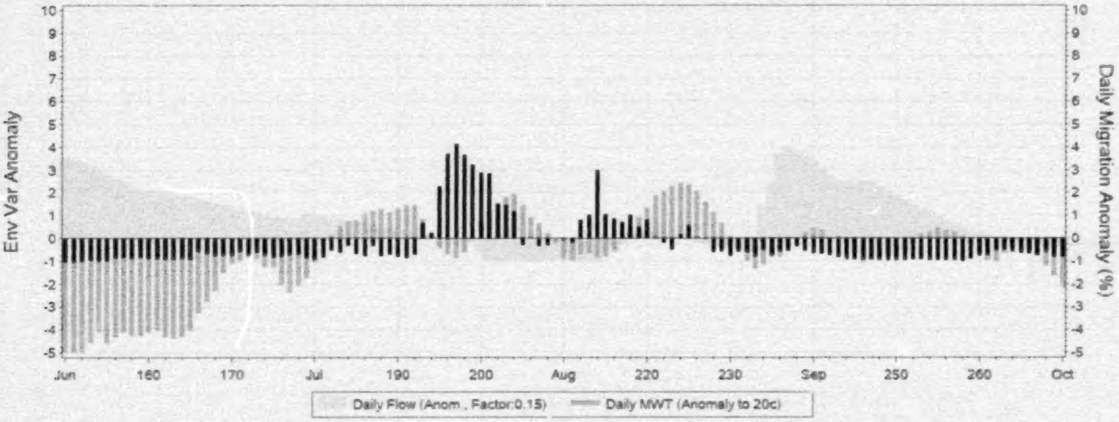
1999 SPR Sockeye Migration Conditions: PDO/ENSO: Cool/Cool Jun-Sep MWT: 19.6c Total Migrants: 169635.93443
Zero-Line Thresholds: Daily Migrants: 1.07% MWT: 20c Flow: 10 cms



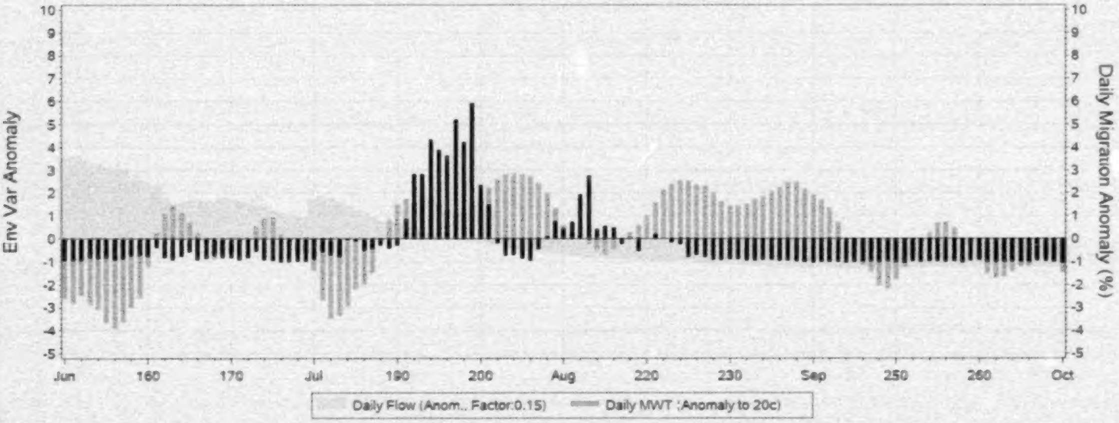
2000 SPR Sockeye Migration Conditions: PDO/ENSO: Cool/Cool Jun-Sep MWT: 19.7c Total Migrants: 126339
Zero-Line Thresholds: Daily Migrants: 1.07% MWT: 20c Flow: 10 cms



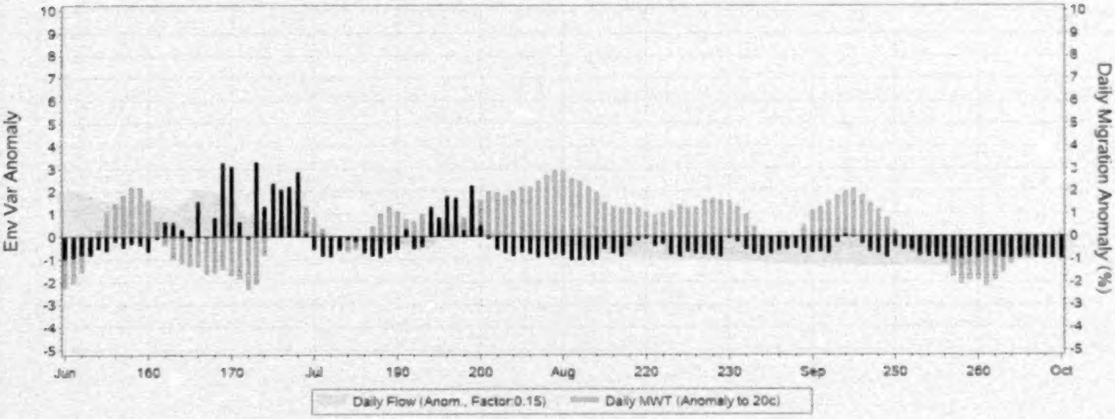
2001 SPR Sockeye Migration Conditions: PDO/ENSO: Cool/Neutral Jun-Sep MWT: 19.3c Total Migrants: 371518
Zero-Line Thresholds: Daily Migrants: 1.07% MWT: 20c Flow: 10 cms



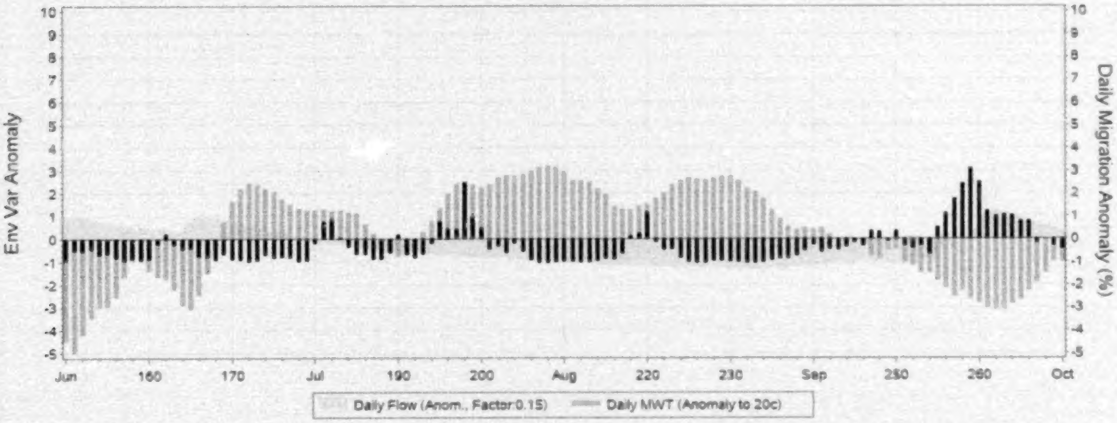
2002 SPR Sockeye Migration Conditions: PDO/ENSO: Cool/Neutral Jun-Sep MWT: 20.0c Total Migrants: 220189
Zero-Line Thresholds: Daily Migrants: 1.07% MWT: 20c Flow: 10 cms



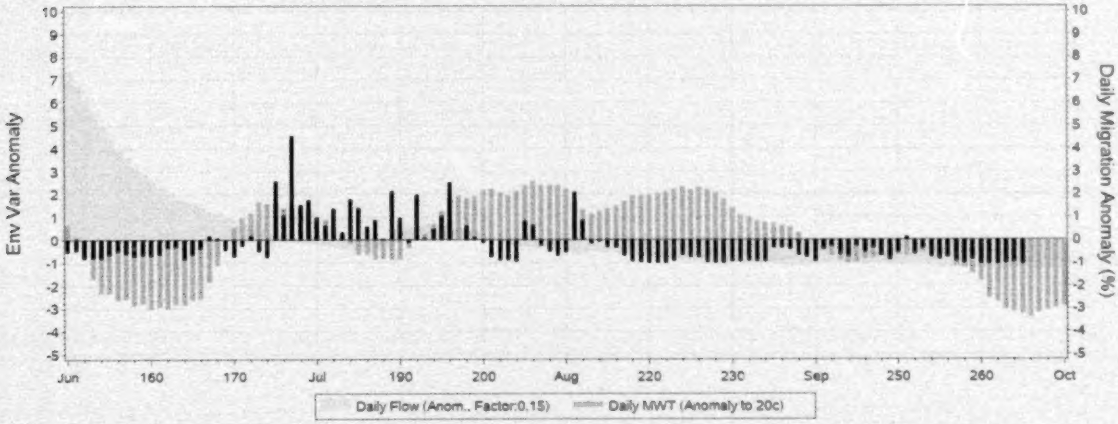
2003 SPR Sockeye Migration Conditions: PDO/ENSO: Warm/Warm Jun-Sep MWT: 20.4c Total Migrants: 189001
Zero-Line Thresholds: Daily Migrants: 1.07% MWT: 20c Flow: 10 cms

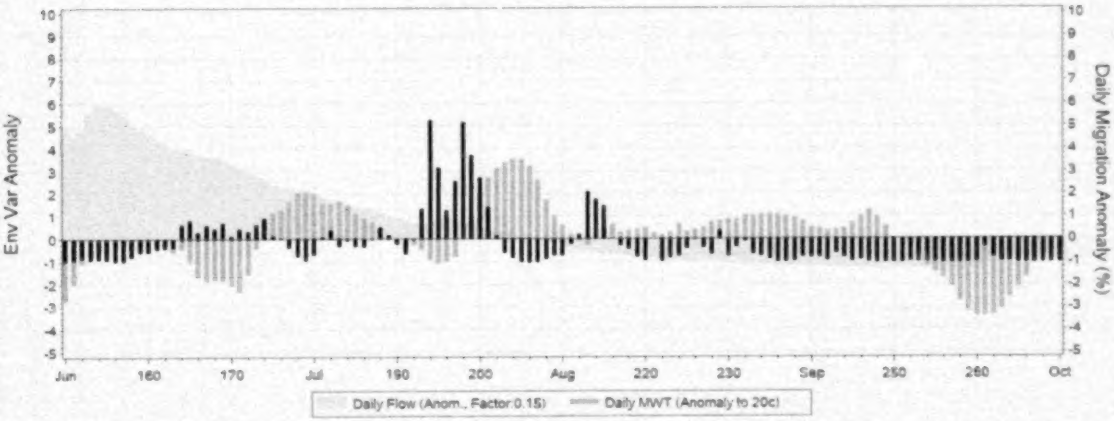


2004 SPR Sockeye Migration Conditions: PDO/ENSO: Warm/Warm Jun-Sep MWT: 20.2c Total Migrants: 149947
Zero-Line Thresholds: Daily Migrants: 1.07% MWT: 20c Flow: 10 cms

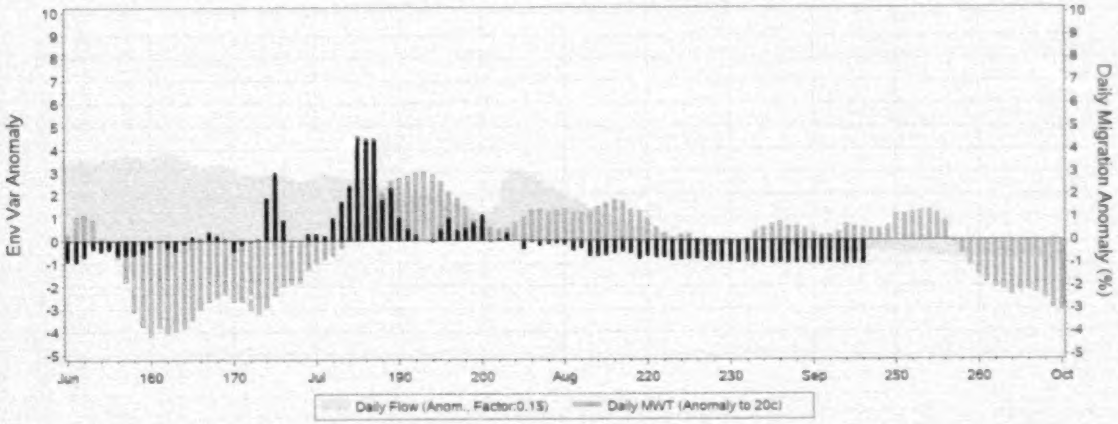


2005 SPR Sockeye Migration Conditions: PDO/ENSO: Warm/Warm Jun-Sep MWT: 19.9c Total Migrants: 150568
Zero-Line Thresholds: Daily Migrants: 1.07% MWT: 20c Flow: 10 cms

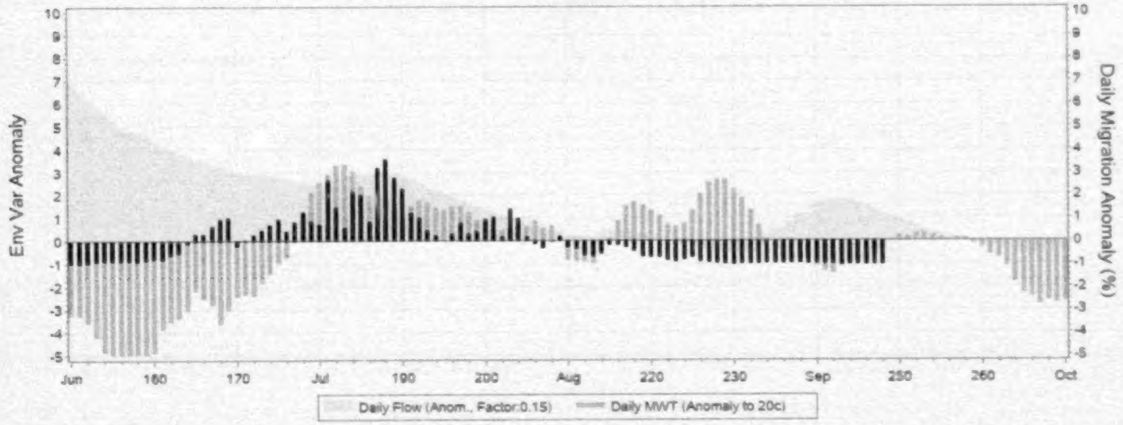




2006 SPR Sockeye Migration Conditions: PDO/ENSO: Cool/Neutral Jun-Sep MWT: 20.0c Total Migrants: 63357
Zero-Line Thresholds: Daily Migrants: 1.07% MWT: 20c Flow: 10 cms

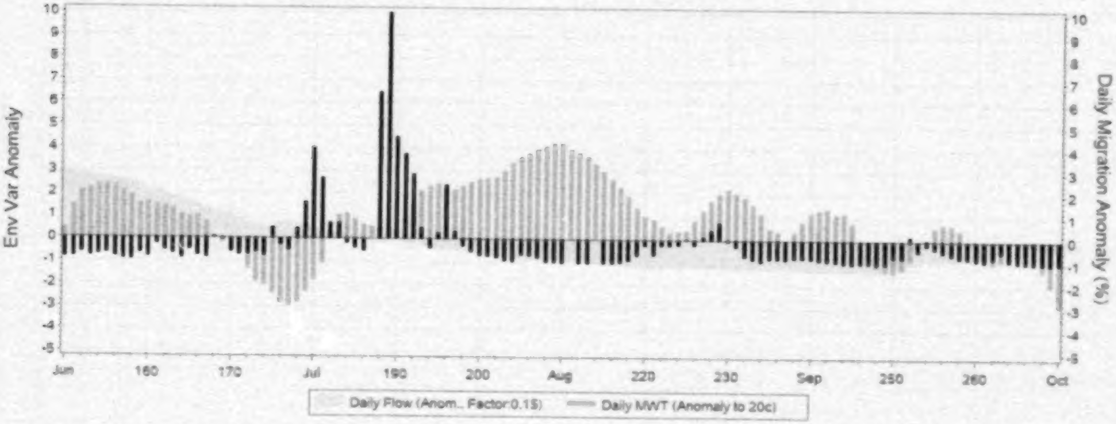


2007 SPR Sockeye Migration Conditions: PDO/ENSO: Cool/Warm Jun-Sep MWT: 19.8c Total Migrants: 71975
Zero-Line Thresholds: Daily Migrants: 1.07% MWT: 20c Flow: 10 cms

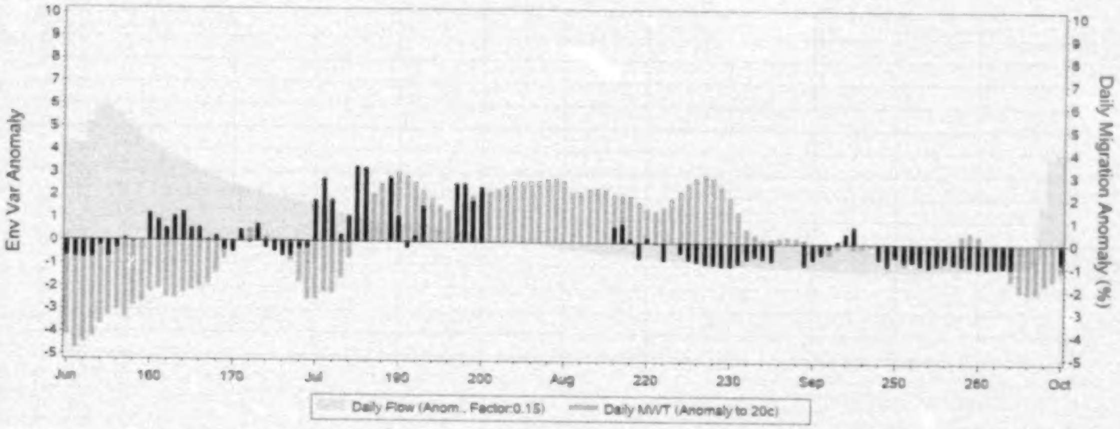


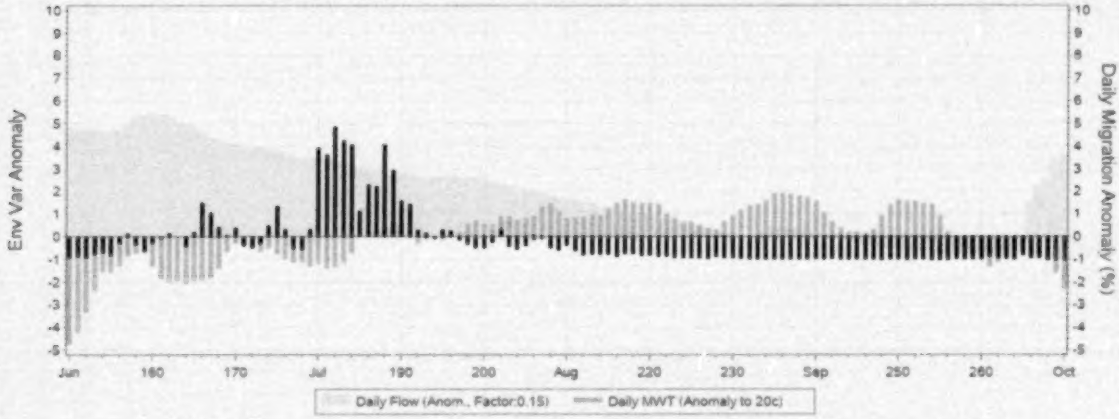
2008 SPR Sockeye Migration Conditions: PDO/ENSO: Cool/Cool Jun-Sep MWT: 19.5c Total Migrants: 116844
Zero-Line Thresholds: Daily Migrants: 1.07% MWT: 20c Flow: 10 cms

2009 SPR Sockeye Migration Conditions: PDO/ENSO: Cool/Neutral Jun-Sep MWT: 20.8c Total Migrants: 177831
Zero-Line Thresholds: Daily Migrants: 1.07% MWT: 20c Flow: 10 cms

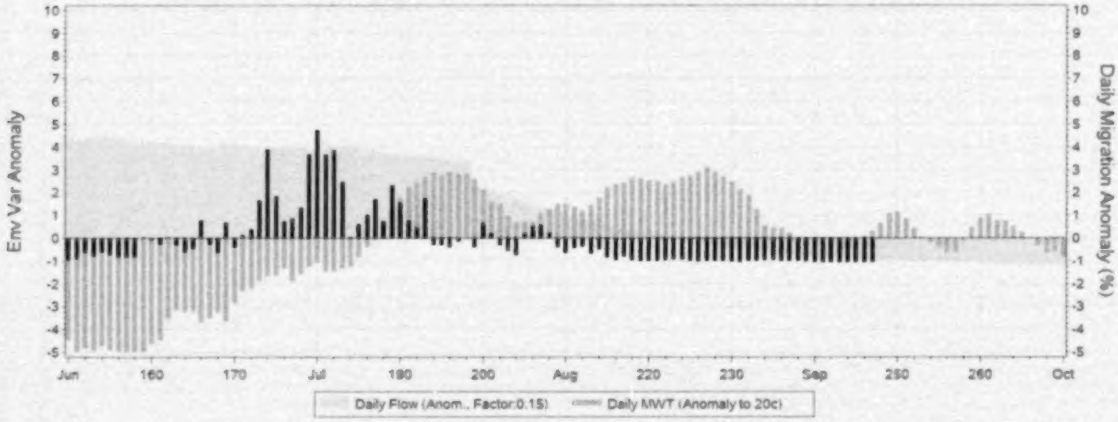


2010 SPR Sockeye Migration Conditions: PDO/ENSO: Warm/Warm Jun-Sep MWT: 20.1c Total Migrants: 275468
Zero-Line Thresholds: Daily Migrants: 1.07% MWT: 20c Flow: 10 cms





2011 SPR Sockeye Migration Conditions: PDO/ENSO: 2011/Unknown Jun-Sep MWT: 20.0c Total Migrants: 439214
Zero-Line Thresholds: Daily Migrants: 1.07% MWT: 20c Flow: 10 cms



2012 SPR Sockeye Migration Conditions: PDO/ENSO: 2012/Unknown Jun-Sep MWT: 20.1c Total Migrants: 229755
Zero-Line Thresholds: Daily Migrants: 1.07% MWT: 20c Flow: 10 cms